2018

Physical Sciences

STRATEGIC PLAN

BERKELEY LAB

BERKELEY LAB
PHYSICAL SCIENCES

On the cover, clockwise from top:

The Berkeley Lab Laser Accelerator Center (BELLA) develops ultra-compact laser-plasma particle accelerators. Electron beam energies greater than 4 GeV have been achieved in just 9 cm, a much higher gradient than achievable with conventional accelerators (page 42).

Maurice Garcia-Sciveres works with undergraduate intern Mayra Lopez-Thibodeaux on the integration of a FE-I4 pixel readout chip with a gas Time Projection Chamber (TPC) detector (page 20).

The Berkeley Lab-managed Cryogenic Underground Observatory for Rare Events (CUORE) will search for a never-before-seen particle transformation that could explain the abundance of matter in the universe (page 25).

In our magnetic measurement facility, Erik Wallén and Laura Garcia Fajardo examine a soft-X-ray undulator module for the Linac Coherent Light Source II (LCLS-II) project (page 53).

Inside cover:

Panoramic view of the Lawrence Berkeley National Laboratory (Berkeley Lab), situated in the hills adjacent to the University of California, Berkeley campus and across the Bay from San Francisco.

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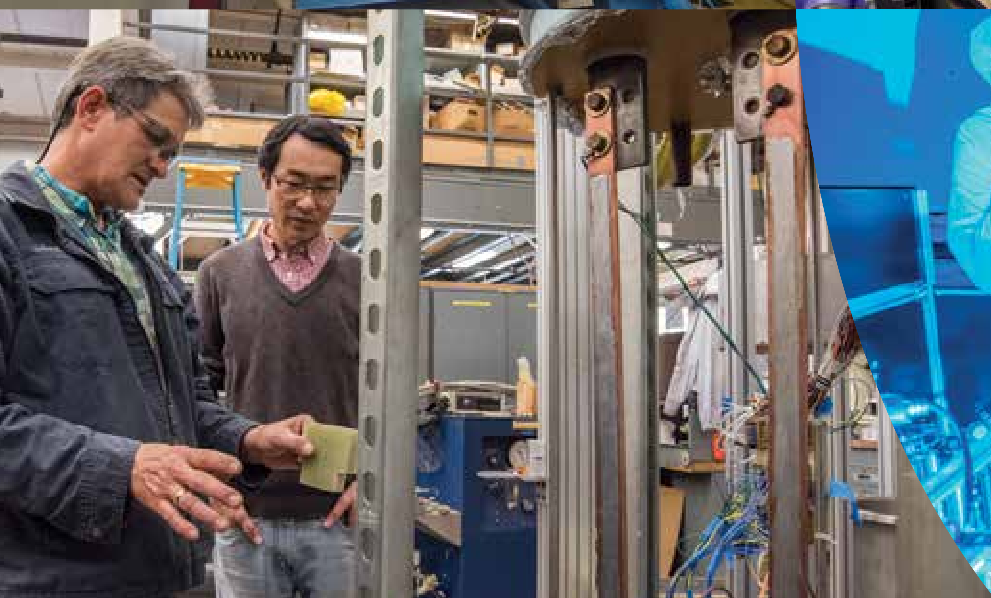


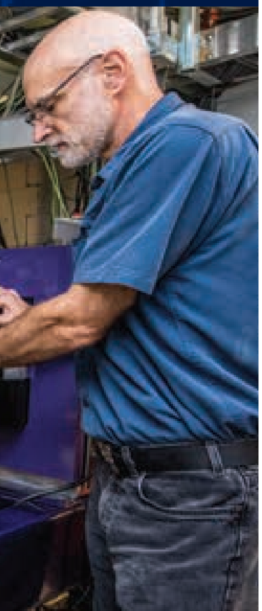
Top left: A view inside the dome at the Mayall Telescope near Tucson, Arizona. The 2-meter corrector barrel atop the telescope is currently being removed and replaced with a new corrector barrel for the Dark Energy Spectroscopic Instrument (DESI). *Photo credit: P. Marenfeld and NOAO/AURA/NSF.*

Top right: Jacklyn Gates and Kenneth Gregorich work on FIONA, a new instrument to measure the mass numbers of superheavy elements that are heavier than uranium.

Bottom left: Hugh Higley (l.) and Xiaorong Wang work on an advanced prototype of a superconducting undulator for future light sources.

Bottom right: Jeroen van Tilborg (l.), graduate student Fumika Isono, and postdoctoral scholar Samuel Barber set up an experiment at the Berkeley Lab Laser Accelerator (BELLA) Center.

Background: Bubble chambers to capture the tracks of particles are part of Berkeley Lab's long heritage in high energy and nuclear physics.



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INTRODUCTION

In the Physical Sciences Area at Lawrence Berkeley National Laboratory (Berkeley Lab), we study the constituents of matter and energy at distances ranging from the innermost confines of subatomic particles to the large-scale structure of the cosmos. This pursuit of fundamental discovery science has been a core strength of our laboratory since it was founded by Ernest Lawrence in 1931. Across the disciplines in the area, we have a diverse and exciting program in experiment, theory, computing and instrumentation, which is well matched to national priorities. These priorities guide our current activities and inform our long-term strategy as we seek to answer questions about the nature of our universe.

In 1941, the Lab broke ground for the 184-Inch Cyclotron on its new site above the UC Berkeley Campus. Here, Ernest Orlando Lawrence addresses the staff.

On the frontiers of high energy physics, we are executing the roadmap described in the most recent High Energy Physics Advisory Panel Particle Physics Project Prioritization Panel (P5) Report, published in 2014. Berkeley Lab is leading the construction of two experiments that will provide new insights into two of the great scientific mysteries of our time: dark matter and dark energy. We are also playing an important role in the high luminosity upgrade of the Large Hadron Collider (LHC) at CERN, which we will exploit to study the properties of the Higgs boson and search for new phenomena beyond the standard model of particle physics.

For nuclear physics, guided by the 2015 *Long Range Plan for Nuclear Science*, we are building a unique gamma-ray spectrometer which will be installed at the Facility for Rare Isotope Beams (FRIB), a new research center at Michigan State University that will turn on in 2022. Measurements of unstable nuclei using this instrument will be essential in understanding remarkable events on the new frontier of multi-messenger astronomy. We are also participating in the upgrade of the heavy ion experiment at the LHC.

In the field of accelerator science, we are developing new compact laser plasma accelerators that could transform accelerator-based science of all types as dramatically as did Lawrence's invention of the cyclotron. By shrinking the footprint of accelerator facilities, laser plasma technology will enable a number of new applications ranging from medical treatment to homeland security. We are also developing new types of superconducting high-field magnets to enable future colliders to reach even higher energies.

Throughout these broad-ranging efforts, we are guided by the team approach that was one of Lawrence's greatest contributions to science. He believed that the inclusion of professional engineers, and sound engineering practice, had a more profound effect on progress than that of any individual scientist. This is still true today. The advanced engineering, unique technical capabilities, and strong project management to be found within our area ensure that we contribute effectively to the national program as we design, build and operate new experiments.

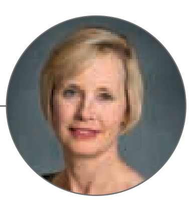
In our work, we collaborate actively with many laboratories and universities around the world. However, we are particularly fortunate to have a close partnership with UC Berkeley. This has been a unique strength of the Laboratory from the beginning. The strong engagement of faculty and students in our programs brings new ideas, trains the next generation of scientists, and creates an intellectually stimulating environment that makes it a pleasure to work here.

James Symons
Associate Laboratory Director for Physical Sciences

Wim Leemans
Division Director, Accelerator Technology and Applied Physics

Henrik von der Lippe
Division Director, Engineering

Barbara Jacak
Division Director, Nuclear Science



Natalie Roe
Division Director, Physics

BERKELEY LAB PHYSICAL SCIENCES

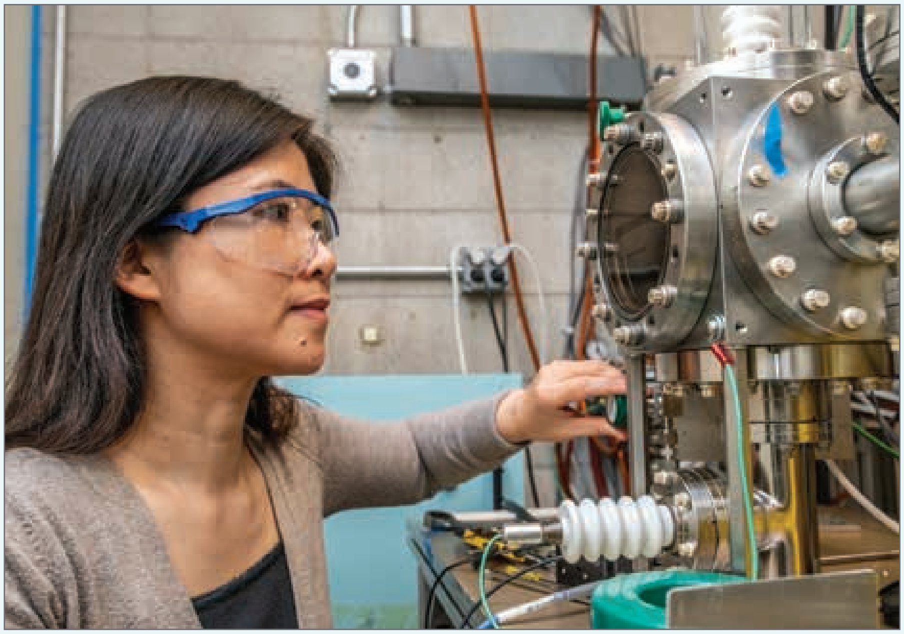
Berkeley Lab's Accelerator Technology & Applied Physics Division (ATAP), Engineering Division, Nuclear Science Division (NSD), and Physics Division make up the Physical Sciences Area. There are many powerful synergies among our four Divisions, and we are also connected to other science areas at the Laboratory, especially *Computing Sciences* and *Energy Sciences*.

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION

ATAP invents, develops, and deploys advanced particle accelerators and photon sources to explore and control matter and energy. ATAP explores the frontiers of accelerator and photon-source science, advances the applications of accelerator-produced beams, and provides powerful new tools to serve the nation's needs. These capabilities have helped make ATAP the partner of choice in many of the most demanding projects throughout the DOE complex and worldwide, including the High-Luminosity LHC, Linac Coherent Light Source II (LCLS-II), and Advanced Light Source-Upgrade (ALS-U). ATAP operates the Berkeley Lab Laser Accelerator (BELLA) Center and, together with Engineering Division, the Berkeley Center for Magnet Technology (BCMT) and is headquarters of the U.S. Magnet Development Program (USMDP). The Division also has focused expertise in accelerator controls and instrumentation (including laser technology innovations), accelerator modeling, fusion science and ion beam technology.

ENGINEERING DIVISION

Engineering provides a broad range of unique capabilities and multidisciplinary engineering expertise needed to address critical scientific problems of global impact. A unique resource for the Lab and scientific community, the Engineering Division provides high-quality, technically advanced, comprehensive electrical and mechanical manufacturing resources. These are deployed in support of the development, construction, and operation of unique scientific products, projects, programs, and user facilities. Engineering performs advanced and specialized design and fabrication, and engages in mutually advantageous partnership with the private sector.



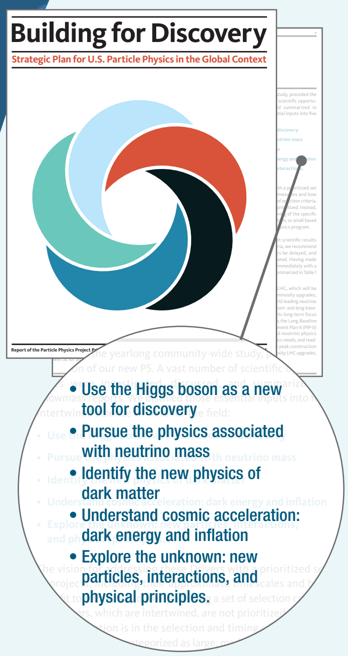
Qing Ji inspects the setup for an experiment on pulsed plasma dynamics.

NUCLEAR SCIENCE DIVISION

The Nuclear Science Division conducts basic research aimed at understanding the structure and interactions of nuclei and the forces of nature as manifested in nuclear matter. NSD has programs in low-energy nuclear science, including nuclear structure physics, studies of the heaviest elements, exotic nuclei and light radioactive beams, weak interactions, and nuclear reactions; relativistic heavy ion physics; nuclear theory; nuclear astrophysics and neutrino properties; data evaluation; and advanced instrumentation. The Division also operates the 88-Inch Cyclotron, which is the home of the Berkeley Accelerator Space Effects (BASE) Facility and supports a local research program in nuclear science. The Division pursues new opportunities in cutting-edge nuclear science, develops advanced radiation detection applications for societal benefits, and furthers science education of the general public and students at all levels.

PHYSICS DIVISION

The Physics Division carries out research that spans the full range of particle physics and cosmology, from studies of subatomic particles to large-scale cosmological structures. Lab physicists conduct research at leading facilities all over the world. At the ATLAS experiment at CERN in Geneva, Switzerland, they are searching for new particles beyond the Standard Model. They also are leading the construction of the underground LUX-ZEPLIN (LZ) experiment in South Dakota that seeks answers about the nature of dark matter, and the Lab is leading the Dark Energy Spectroscopic Instrument (DESI) project that will precisely measure the accelerating expansion of the universe in order to understand the origin of dark energy. Lab physicists also carry out theoretical work on a wide range of topics, develop new types of instrumentation, and lead the Particle Data Group (PDG), which publishes the definitive reference for particle physics.



FIVE AND TEN YEAR PRIORITIES

The Physical Sciences Area has a balanced program of research, instrumentation R&D, and project leadership and execution. We are committed to applying the highest scientific and safety standards with a commitment to a diverse workforce and an equitable and inclusive workplace. We are moving forward on exciting experiments, as well as leading edge technologies, including laser-plasma acceleration, advanced superconducting magnets, and electronics and instrumentation.

The divisions of the Physical Sciences Area are active participants in the planning processes of their disciplines. An iterative process of community workshops and agency guidance, resulted in published strategic documents that express consensus about the R&D priorities of each field. Key documents that guide our efforts include:

- *Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context* (the "P5 Report").
- *Accelerating Discovery: A Strategic Plan for Accelerator R&D in the U.S.,* Accelerator Research and Development Subpanel, DOE High Energy Physics Advisory Panel.
- *Reaching for the Horizon: The 2015 Long-Range Plan for Nuclear Science,* Nuclear Science Advisory Committee.

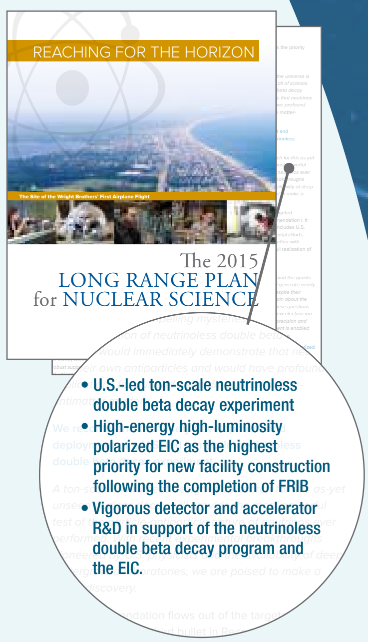
FIVE YEAR HORIZON – SUCCESSFUL EXECUTION OF ONGOING PROJECTS

Within the Department of Energy (DOE) Office of Science, successful execution of large projects is exceptionally important. The life cycle of these projects from identification of need to project completion can easily be a decade or more and is deeply connected to the planning processes described above.

The DOE national laboratories play a key role managing these projects and delivering sophisticated detectors and facilities for the user community. Often, projects make use of the capabilities of many of these laboratories. In the coming five years, much of our attention in our area will be on the following activities.

- Install, operate and obtain the first results from *DESI* and *LZ* to elucidate the nature of dark energy and dark matter.
- Study the inflationary era in the history of the universe at the *Simons Observatory* and participate in the R&D, design and construction of the next major experiment for this field: Cosmic Microwave Background – Stage IV (*CMB-S4*).

- Advance the technology and underlying science of high-field superconducting magnets, which will underpin the design of the next collider facility.
- Construct and install key parts of the high-luminosity upgrade of the LHC accelerator and the ATLAS detector.
- Couple two laser-plasma accelerator stages to achieve high energies using the *BELLA Second Beam Line*; an important milestone for the development of high energy compact accelerators.
- Complete the double-beta decay demonstrators MAJORANA DEMONSTRATOR (*MJD*) and Cryogenic Underground Observatory for Rare Events (*CUORE*) to study the nature of neutrinos and their masses, and determine the most effective technology for next generation detectors.
- Complete the twenty-year study of high energy nuclear matter at the Relativistic Heavy Ion Collider with a beam energy scan that will map out the transition from the normal state of matter to a quark gluon liquid.
- Develop a plan for the key Engineering infrastructure needs of the Laboratory and necessary unique capabilities, such as composites, microelectronics, metrology, additive manufacturing, and clean rooms.



TEN YEAR HORIZON AND BEYOND — LONG TERM ENGAGEMENT IN OUR FIELDS

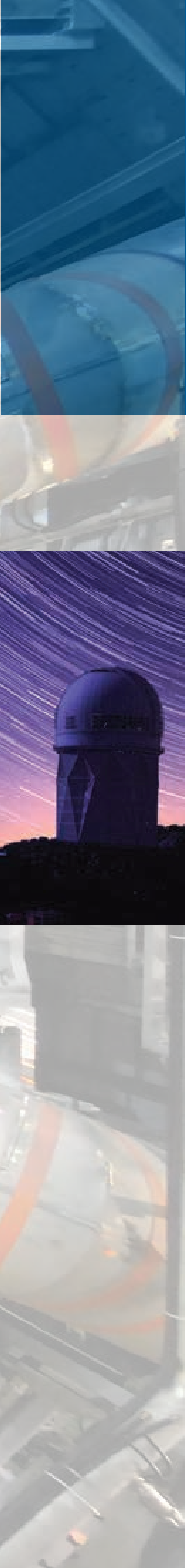
On the ten year horizon, a number of new opportunities will become available.

- The highest priority for new construction in nuclear physics is the Electron-Ion Collider (EIC). In the coming decade, we will prepare for the EIC's transition from concept to project and take on a significant role in detector construction.
- The highest priority for new construction in the P5 plan for high energy physics is DUNE/LBNF, which will commence operations in the late 2020s. We hope to play a leadership role in the construction and operation of the near neutrino detector for DUNE.
- Participate in the design, construction and operations of *CMB-S4*, a phased effort for the next generation of cosmic microwave background research.
- All applications of laser plasma accelerators will benefit from higher repetition rate. Over the next decade we plan to build and install *k-BELLA*, the world's first high average power, high repetition rate laser plasma accelerator facility.
- Complete the modernization of our Engineering facilities to be prepared for the challenges of the 2030s.

Research in particle physics and cosmology is a global effort that seeks to answer some of humankind's biggest questions:

- **What are the fundamental forces of nature?**
- **What are the building blocks of matter?**
- **How did the universe develop into its present form?**

To carry out this discovery science, Berkeley Lab physicists conduct experiments at particle accelerators, such as the massive ATLAS detector at CERN (background image), at nuclear reactors to study neutrino oscillations (left), at the bench to develop new methods and instrumentation (center), and at astronomical observatories to study the structure and evolution of the universe (right).



PARTICLE PHYSICS AND COSMOLOGY

Berkeley Lab has a long tradition of world-leading research in particle physics and cosmology, seeking answers to fundamental questions about the constituents of matter and energy in the universe. Today, this research program is strongly aligned with the recommendations from the 2014 report of the Particle Physics Project Prioritization Panel (P5), *Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context*.

This report identified five compelling lines of inquiry, or "Science Drivers," that show great promise for discovery in the next 10 to 20 years:

- Use the Higgs boson as a new tool for discovery.
- Pursue the physics associated with neutrino mass.
- Identify the new physics of dark matter.
- Understand cosmic acceleration: dark energy and inflation.
- Explore the unknown: new particles, interactions, and physical principles.

The P5 vision is rapidly becoming a reality, with the approval of several new projects that are now in construction. Berkeley Lab is leading two of these experiments and playing significant roles in several others.

REPORT OF THE PARTICLE PHYSICS PROJECT PRIORITIZATION PANEL

After a year-long community process of town-hall meetings and whitepapers, the 25-member P5 panel (which included two members from Berkeley Lab) was charged with developing a draft strategic plan for U.S. particle physics for the next decade and beyond. The P5 Report, which was released in May 2014, has served as a roadmap for the development of the large projects needed for the next generation of discoveries in particle physics. In alignment with this vision, the Berkeley Lab program is poised for a decade of discovery with a number of new projects under construction and about to begin data taking.

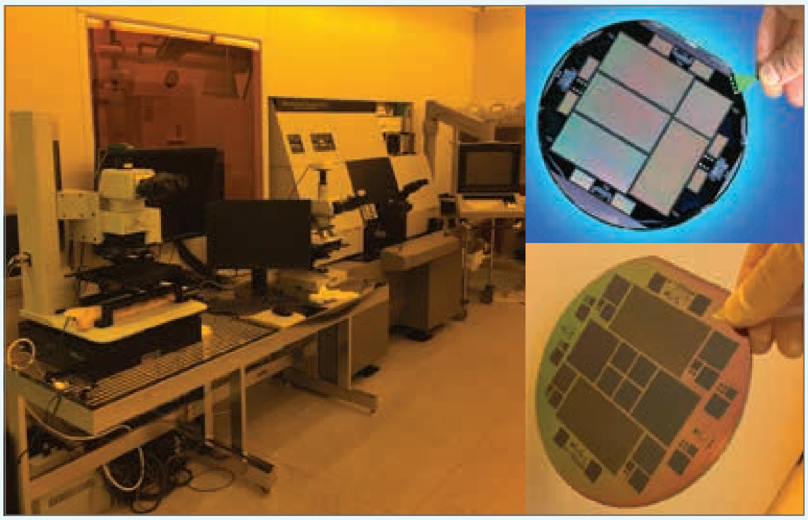
Graduate student Parker Fagrelius inspects ProtoDESI, a prototype system for the Dark Energy Spectroscopic Instrument.

The essential components of the Berkeley Lab physics program of discovery for the coming decade include:

- **Higgs and the Unknown:** Berkeley Lab has a large group using the ATLAS experiment at CERN to study the nature of the Higgs boson and search for new physics produced in high-energy collisions at the Large Hadron Collider (LHC). They also play leading roles in the ATLAS detector upgrades for the High-Luminosity LHC. Berkeley Lab has a smaller, focused role in the Mu2e experiment at Fermilab, which will be sensitive to new physics at much higher mass scales than the LHC.
- **Dark Energy and Inflation:** Berkeley Lab is the lead lab for the Dark Energy Spectroscopic Instrument (DESI) experiment that will map the expansion history of the universe in exquisite precision to study dark energy and test general relativity. Berkeley Lab also participates in the current Stage III cosmic microwave background (CMB) polarization experiments, Simons Array and Simons Observatory, while carrying out R&D toward a future CMB-S4 experiment to detect the faint signals from inflation.
- **Dark Matter:** Berkeley Lab is the lead lab for LUX-ZEPLIN (LZ), the largest, most sensitive detector currently planned for the detection of Weakly Interacting Massive Particle (WIMP) dark matter. Berkeley Lab is also carrying out R&D towards future experiments beyond LZ to explore light dark matter.
- **Neutrinos:** Berkeley Lab has a lead role in the design of the Near Detector for DUNE, building on a long and successful history in neutrino physics with the KamLAND and Daya Bay experiments. The DESI galaxy redshift survey will also shed light on neutrino mass through its contributions to structure formation in the universe.

The unique strengths and capabilities that Berkeley Lab brings to these physics programs include:

- **Detector innovation:** a traditional Berkeley Lab strength that opens new avenues for experimental investigations. We benefit from the mechanical and electrical engineering expertise in the Engineering Division, as well as the Composites Facility and the MicroSystems Laboratory (MSL).
- **Advanced computing:** an increasingly important and enabling component of all HEP research. We leverage expertise at Berkeley Lab's National Energy Research Supercomputing Center (NERSC) and Energy Sciences Network (ESNet) to the benefit of HEP projects, and we collaborate extensively with data scientists in the Computing Research Division and at UC Berkeley.
- **Theoretical studies** directly benefit current experimental efforts at Berkeley Lab and across the broader U.S. program, informing current and proposing future research directions.
- **The Particle Data Group** (PDG), which we lead, produces a comprehensive and respected annual compilation of results together with expert reviews covering all of particle physics and related cosmological measurements.
- **A strong partnership with the Physics and Astronomy Departments at UC Berkeley** brings faculty and students to the lab, leveraging resources and contributing to a stimulating intellectual environment. We place a high priority on mentoring young scientists; dozens of former graduate students and postdoctoral fellows trained at Berkeley Lab now hold faculty or permanent research positions at leading institutes worldwide.



The MicroSystems Laboratory (left) is in a class-10 clean room created for end-to-end fabrication of silicon detectors. Engineer Steve Holland at MSL developed a new type of charged-coupled device, or CCD (upper right), that is more sensitive in the infrared than conventional CCDs. These fully depleted red-sensitive CCDs are now used in all DOE dark energy surveys. Work is currently underway to develop germanium-based CCDs (lower right), which will extend the sensitivity even further in the infrared.

The recently discovered Higgs boson is a form of matter never before observed, opening up many new avenues of investigation:

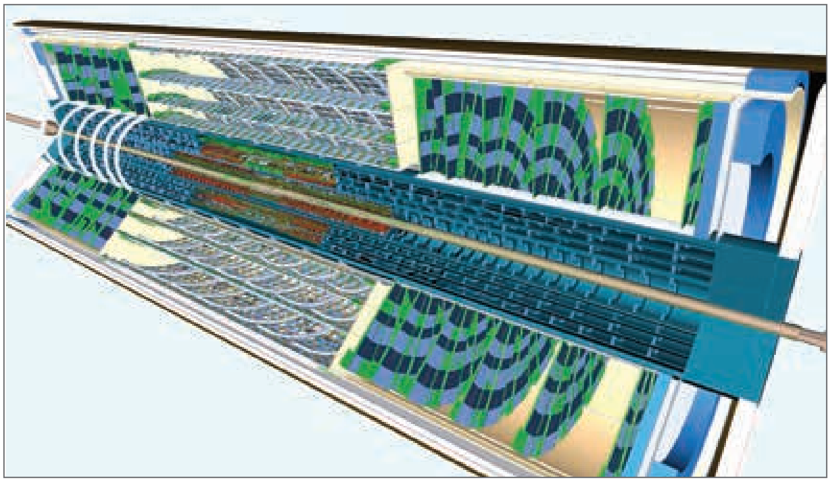
- What determines its effects on other particles?
- Is there one Higgs particle or many?
- Is it related to dark matter?
- Does it couple to dark matter?
- Are there other forms of matter awaiting discovery?

HIGH ENERGY COLLIDER PHYSICS: HIGGS AND EXPLORING THE UNKNOWN

The CERN Large Hadron Collider (LHC) collides protons at the highest energy of any facility. The Berkeley group joined the ATLAS detector collaboration in 1993 and made important contributions to the design and construction of the original detector, which was completed in 2008. A major upgrade of the ATLAS detector will be essential for continued operations in the High-Luminosity LHC (HL-LHC) era. The HL-LHC is scheduled to begin operation in the mid-2020s.

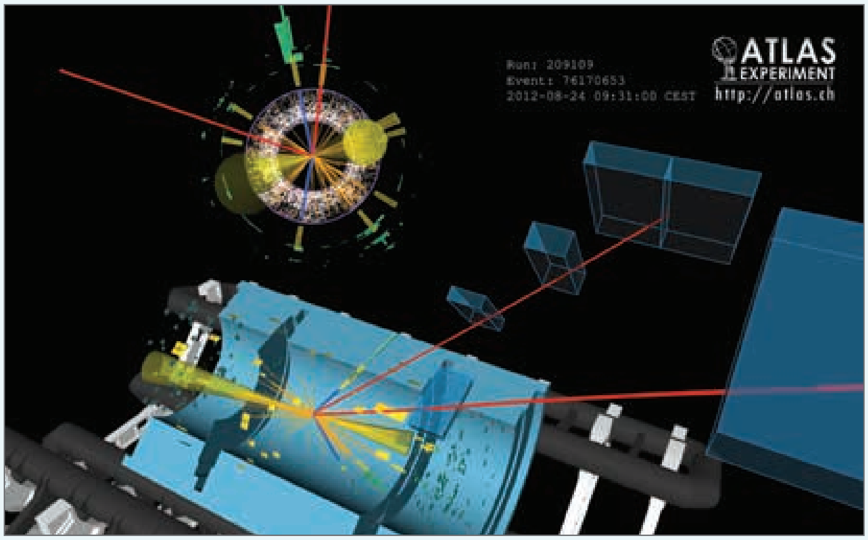
Berkeley Lab's expertise in the silicon detectors that are closest to the interaction point was crucial in the original construction of these precision systems. This expertise has naturally led to leading roles in silicon detector operations, and more recently to major roles in the planned new Phase-2 tracker, the Integrated Tracker (ITk).

The upgraded ATLAS detector will have increased capabilities, enabling more precise measurements in the higher rate environment. Berkeley Lab is the only U.S. lab with simultaneous responsibilities on ATLAS strips, pixels, and mechanics. These efforts depend on technical and engineering efforts, including IC design expertise from the Engineering Division. We also work closely with colleagues in the Computing Research Division to design and maintain the software infrastructure and simulation of the detector, which play a vital part in data analysis.



Design of the new Inner Tracker Detector for the ATLAS experiment. Berkeley Lab scientists have lead roles in the design of this silicon detector, which is needed for ATLAS to operate in the very demanding environment of the High-Luminosity upgrade of the CERN Large Hadron Collider.

Postdoc Aleksandra Dimitrievska works on prototype chips for the ATLAS detector upgrade.



Display of a Higgs boson decay in the ATLAS detector. The Higgs boson candidate, produced at the interaction point, decays into two electrons (blue lines) and two muons (red lines).
Image courtesy CERN.

After contributing to the discovery of the Higgs boson in 2012, the Berkeley Lab ATLAS group has been concentrated on measuring its couplings to other particles and to the search for new particles, such as those that could account for dark matter. When fully realized around the mid-2020s, the HL-LHC will deliver data at 10 times the current rate, enabling very rare processes to be studied in detail. Interactions between the ATLAS group and the Berkeley theory group through monthly joint seminars are important in generating new ideas in the search for new physics.

Neutrino physics has progressed dramatically over the past two decades. However, open questions remain, and these are among the most compelling questions in particle physics:

- Is CP symmetry violated in neutrino oscillation?
- What is the correct mass hierarchy?
- What is the sum of neutrino masses?
- Does a light sterile neutrino exist?

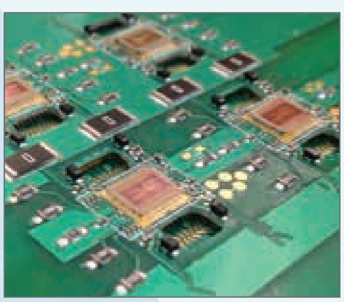
NEUTRINO PHYSICS

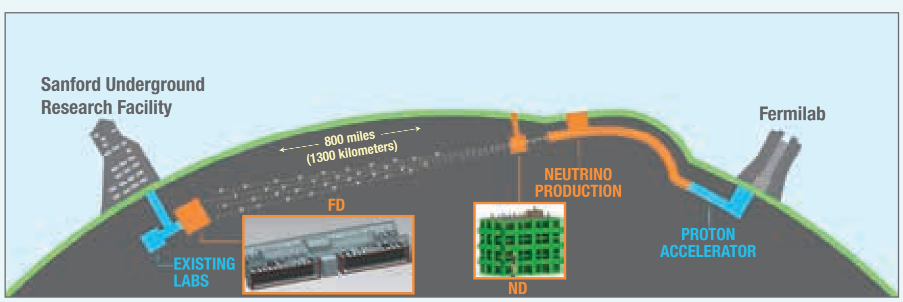
Through experiments at reactors, accelerators, and cosmological observations, Berkeley Lab Physics Division researchers are developing new methods to tackle the questions described in the sidebar at left.

The discovery of neutrino oscillations in the late 1990s opened a new realm of exploration into the three mixing angles and the neutrino masses. Berkeley Lab scientists had leadership roles in the KamLAND experiment, which observed neutrino oscillations in reactor anti-neutrinos and made the first observation of geo-neutrinos (neutrinos from Earth's interior). We then led the U.S. contributions to construction, operation, and data analysis of the Daya Bay experiment, which made the first measurement of the mixing angle, θ_{13}, and has investigated other properties of neutrinos including potential sterile neutrinos. This work has been recognized with a number of prizes and awards.

The DUNE experiment, which will direct an intense neutrino beam from Fermilab to a very large liquid argon TPC detector located underground in South Dakota, will be the flagship experiment for the U.S. neutrino program for the next 10 to 20 years. A critical component of this experiment is the Near Detector (ND) at Fermilab to characterize the neutrino beam. Berkeley Lab has a prominent role in the design of the DUNE ND, with plans to continue into the construction and commissioning phases. We are also contributing expertise to the design of the cold electronics inside the cryogenic detector for the Near and Far Detectors, and are designing a pixel readout chip for the ND. The software for DUNE requires the development of sophisticated algorithms and a powerful computing infrastructure. Berkeley Lab physicists, together with computer scientists from the Computing Research Division and NERSC, are actively involved in the software design.

Finally, the DESI experiment, described in more detail below, will provide entirely complementary constraints on the sum of the neutrino masses from a detailed map of the growth of cosmic structure.





Berkeley Lab leads the design of the Near Detector for the DUNE/LBNF experiment. The Lab is also developing cryogenic pixelated readout integrated circuit for improved pattern recognition and tracking capabilities.

RARE PROCESSES – EXPLORING THE UNKNOWN

One possible signature for new physics would be the observation of charged lepton flavor violation – for example, a muon changing to an electron. Charged lepton-flavor transition without neutrino emission has never been observed, but it is predicted by most Beyond the Standard Model (BSM) theories. The Mu2e experiment, which is under construction at Fermilab, will search with unprecedented sensitivity for muon conversion into an electron in the field of a nucleus.

Postdoc Richie Bonventre (right), with collaborators from Rice University and the University of Minnesota, works on the Mu2e straw chamber tracker at Fermilab. *Image courtesy Fermilab.*

Berkeley Lab is making major contributions to the Mu2e experiment in design of the tracker, electronics, triggering, calibration, and overall software design. Data taking for the experiment is expected to begin early in the next decade, and it is anticipated that it will reach its advertised sensitivity after about three years of operation.

In addition, the ATLAS group, as described above, will actively search for signs of new physics and rare processes with data being collected now and in the next decade when the upgraded detector is installed and taking data at the HL-LHC.

The key questions surrounding dark energy and inflation include:

- What is driving the accelerated expansion of the universe today?
- Is it caused by the energy in the vacuum, the so-called cosmological constant, and if so, why is the cosmological constant so small?
- Is cosmic acceleration driven by a different type of dark energy that evolves with time?
- What drove the apparent accelerated expansion during the inflationary epoch at ultrahigh energies?

A rendering of the Dark Energy Spectroscopic Instrument (DESI) mounted on the Kitt Peak Mayall telescope. Light from galaxies and quasars will be collected at prime focus by 5,000 robotically positioned fibers and fed to 10 spectrographs.

DARK ENERGY AND INFLATION

The experimental cosmology program at Berkeley Lab, in partnership with the UC Berkeley cosmology group, forms one of the leading centers for cosmological studies in the world, focused on:

- Type Ia Supernovae (SNe)
- Large-scale structure of the universe using spectroscopic surveys
- CMB polarization measurements

Together, these three techniques provide complementary, robust, and sensitive probes to study the composition and evolution of the universe. Within each domain,we have a mix of current projects that are taking data and new projects under construction, so the roadmap for the next 10 years is clearly established.

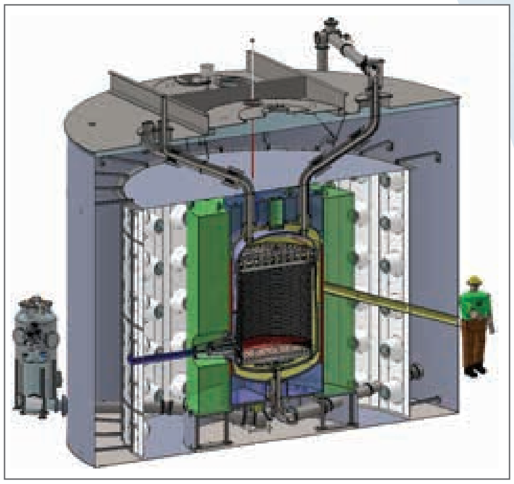
Our Type Ia SNe group discovered dark energy in the late 1990s and continues to study SNe from ground- and space-based telescopes to improve the measurement of dark energy and extend it to higher redshifts. Over the next decade, we will be developing a program using the Large Synoptic Survey Telescope (LSST) to identify SNe that can be subsequently observed with other telescopes in order to obtain spectroscopic typing and redshifts. The spectroscopic follow-up will provide a well-calibrated, precision sample for probing dark energy.

Berkeley Lab's role in charting the large-scale structure of the universe goes back to 2005, when we proposed and led the BOSS experiment, which went on to establish baryon acoustic oscillations (BAO) as a precision technique to chart the effects of dark energy. Our current focus is on completing the construction of the Dark Energy Spectroscopic Instrument (DESI), a Stage IV BAO experiment to create the largest 3D map of the universe, with over 30 million galaxies. DESI will be installed on the Mayall telescope at Kitt Peak, Arizona, and will conduct a five-year survey that will extend through the middle of the next decade. Planning for the post-DESI era is underway, and could include an extension of the survey, an upgrade of the instrument, and/or moving DESI to a telescope in the Southern Hemisphere.

The CMB polarization program is building on the infrastructure being developed at currently operating experiments in Chile leading up to the proposed next-generation experiment, CMB-S4. We are carrying out detector and readout R&D to advance the necessary technologies for both the Simons Observatory and CMB-S4, and developing the large-scale simulations necessary for planning and analyzing CMB-S4 based on prior computational work carried out for the Planck mission. The Berkeley Lab CMB effort is a phased program that will extend well through the next decade.

DARK MATTER

Astrophysical observations stretching back at least 50 years, including recent studies of the behavior of stars and galaxies, have clearly established that about three-quarters of the mass and energy of the entire universe is dark energy, and one-fifth is dark matter, leaving only about 5 percent for normal baryonic matter. Dark matter is invisible to observations across the optical spectrum, and is observed primarily by its gravitational effects. Without the binding effects of dark matter, the galaxies would not have formed, the stars would not shine, and life would not exist.



Cutaway drawing of the LZ experiment, showing the liquid xenon TPC in the center, surrounded by a liquid scintillator veto and water shielding. LZ is under construction and will operate a mile underground in the SURF facility in South Dakota.

Extensive studies suggest that dark matter must be some exotic form of matter not previously observed. Theoretical models favor Weakly Interacting Massive Particles (WIMPs) as an attractive candidate. Over the past 20 years, scientists at Berkeley Lab have designed and developed the well-shielded environment needed to host experiments to search for WIMPs, resulting in the creation of the Sanford Underground Research Facility (SURF). Berkeley Lab was the lead lab for the LUX experiment located at SURF's 4,850-foot level, nearly a mile underground. LUX led the world's searches for WIMPs from its first results in 2013 until the experiment was decommissioned in 2016.

Berkeley Lab now leads the LUX-ZEPLIN (LZ) experiment, which will be installed in the SURF laboratory space formerly occupied by LUX. LZ is a strong international collaboration, numbering over 250 scientists and engineers, and is one of the two major Generation 2 experiments sponsored by the Department of Energy (DOE) and National Science Foundation (NSF). We are also actively developing new detectors for the next generation of dark matter experiments beyond LZ, including the search for light dark matter models proposed by our theory group.

Graduate student Lucie Tvrznikova preparing a cryogenic detector system for liquid xenon R&D. Berkeley Lab has a strong record of integrating undergraduate, graduate students and postdoctoral fellows into all phases of its experimental program — from detector design and construction through data analysis using Berkeley Lab's National Energy Research Supercomputing Center (NERSC) resources.

We explore what the most elementary constituents of matter are, how they interact, as well as the nature of space and time.

What is the particle physics nature of dark matter? Is it a single particle or a more complicated sector?

What is the origin of the asymmetry between matter and antimatter?

Are neutrinos their own antiparticles, and can we understand their tiny masses?

Are there additional particles and interactions that we can probe at the LHC and other colliders?

THEORETICAL PHYSICS

The particle theory group aims to develop groundbreaking new theoretical concepts, methods, calculational tools, and to connect these results with the experiments at Berkeley Lab and worldwide experimental programs. An essential aspect of the group is being a part of the Berkeley Center for Theoretical Physics, a joint research center of the UC Berkeley Physics Department and the Berkeley Lab Physics Division.

The proximity of Berkeley Lab and UC Berkeley, which is within easy walking distance, makes for a world-leading center for theoretical work on elementary particle phenomenology. This unique environment results in exceptional strength in a wide spectrum of research directions, in both high-energy experiment and theory. Daily interactions, joint seminars, and workshops provide an exceptional environment for conducting theoretical physics research. The group is also a center of excellence for training the next generation of theoretical physicists, with many of the group's former postdocs and students holding prominent positions worldwide.

The theory group continues its engagement with the experimental groups in the search for new physics at the LHC and in precision lepton and quark flavor physics. The group also continues to pursue new ideas and methods toward the direct detection of dark matter, extending capabilities of existing experiments and proposing new ones, and responding to new experimental results as they emerge.

Kathryn Zurek explores theoretical models for physics beyond the Standard Model.

ADVANCED COMPUTING FOR HIGH-ENERGY PHYSICS

High-energy physics and cosmology are entering a challenging and exciting period over the next decade, in which current and future experiments pose major computational challenges. Complex datasets are being produced with enormous data volumes, and simulations also require massive computational efforts. The Physics Division partners with NERSC, the Computing Research Division, and UC Berkeley data science institutes to address these exciting challenges.

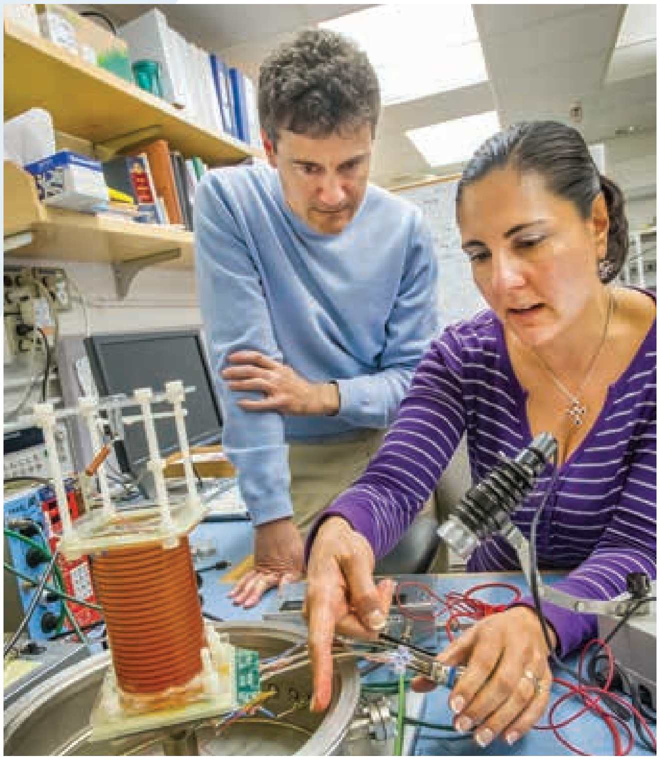
Computing is now deeply embedded in all efforts in experimental and theoretical physics at Berkeley Lab. Physicists work closely with computer science researchers to make new computing architectures accessible and usable for the broader high energy physics community by facilitating use of High Performance Computing (HPC) facilities for particle physics and cosmology experiments. We support cutting-edge R&D into advanced concepts such as machine learning that are being intensely applied to the analyses of data from physics experiments.

PARTICLE DATA GROUP

The Particle Data Group (PDG) provides a regularly updated authoritative and comprehensive summary of particle physics and related areas of cosmology. PDG's primary publication, the *Review of Particle Physics* (RPP), is the most cited publication in particle physics. The PDG is a large, international collaboration of contributors, led by a core group at Berkeley Lab that provides the scientific leadership, central coordination, and technical expertise for the collaboration.

As it has for the past 60 years, the PDG remains focused on producing the RPP as a summary of particle physics and related areas of cosmology. The range of topics it covers is adapted to new developments in the field. A transition from a print-oriented publication to primarily electronic distribution has begun and will evolve in the coming decade.

The *Review of Particle Physics* has grown in size over the years, from a slim volume (bottom) to a massive tome (top). In 2016, the printed edition (upright) contained only part of the review, with the detailed tables available online.



Maurice Garcia-Sciveres works with undergraduate intern Mayra Lopez-Thibodeaux on the integration of a FE-I4 pixel chip readout with a gas Time Projection Chamber (TPC) detector.

DETECTOR R&D

A critical element of Berkeley Lab's leadership in particle physics and cosmology has been the development of advanced detectors. The Time Projection Chamber (TPC) concept originally developed at Berkeley Lab has been widely adopted, not only for gaseous tracking applications, but also for cryogenic liquid detectors that search for dark matter and detect neutrinos and other rare processes. Red-sensitive charge-coupled devices (CCDs) were invented in Berkeley Lab's MicroSystems Lab and are the technology of choice for all current and next-generation dark energy experiments. Customized Application Specific Integrated Circuits (ASICs) for silicon vertex detector strips and pixel readout were pioneered here, and Berkeley Lab continues to play a significant role in this area for particle physics experiments. Advanced composites that have superior mechanical properties and good thermal conduction have been developed at Berkeley Lab in collaboration with industry and are now key components of the tracking upgrade for the ATLAS experiment at the LHC. Berkeley Lab also developed detectors and a frequency multiplexed readout for CMB measurements, equipment being used for current and future experiments.

The Physics Division Detector Development group continues to invest in "blue sky" R&D, looking toward the future in anticipation of the next breakthrough that will enable future high-energy physics experiments. Recent examples include R&D on germanium-based CCDs, low-power pixelated readout for cryogenic TPCs, silicon devices with improved efficiency for vacuum ultraviolet (VUV) detection in noble liquid cryogenic detectors, technology for very-low-energy (sub-eV) threshold detectors with no dark count, etc. In most of its R&D efforts, the Physics Division partners closely with the Engineering Division and utilizes Labwide resources such as the IC Group, the main shops, the Composites Facility, and the Molecular Foundry.

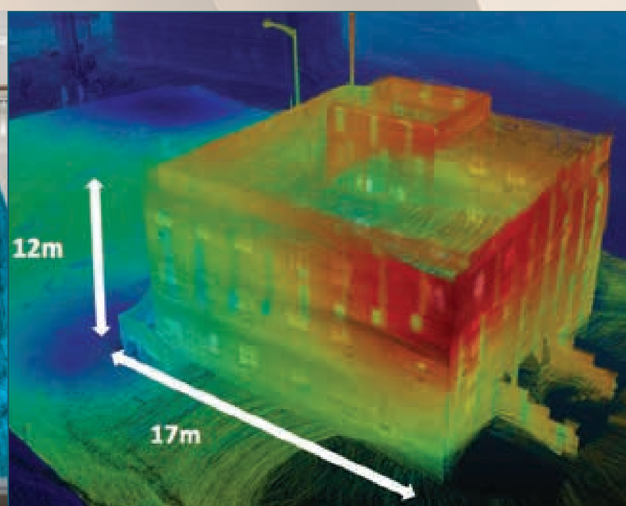
PHYSICS DIVISION FUTURE GOALS

5 YEAR GOALS

- Carry out precision Higgs measurements and searches for new physics with ATLAS Run 2 data.
- Design and build silicon pixel and strip modules and composite support structures for the ATLAS HL-LHC ITK upgrade.
- Design the DUNE ND and contribute to the construction of DUNE ND and cold electronics.
- Contribute to the Mu2e commissioning, first data taking, and analyses.
- Install, commission, and begin the DESI survey.
- Install, commission, and begin the first LZ data run.
- Begin construction on the CMB-S4 experiment.
- Move data processing, simulation, and analysis for all Physics Division projects to NERSC and apply advanced computing techniques.
- Publish new theoretical analyses to guide current and future research.
- Continue the important work of the Particle Data Group and make it even more accessible.
- Make important R&D breakthroughs on future detection technology and techniques.

10 YEAR GOALS

- Observe signs of new physics at the HL-LHC, or set the most stringent limits possible.
- Commission the DUNE ND and begin data taking with the first installed DUNE Far Detector.
- Complete the Mu2e experiment and publish final results on the search for muon conversion to an electron.
- Find evidence for WIMP dark matter with the complete data set from the LZ experiment, or rule out the WIMP hypothesis in most models.
- Finish the DESI survey and publish the most precise measurements of dark energy and its evolution over cosmic time to determine if it is due to a cosmological constant or not.
- Make a convincing detection of the sum of the neutrino masses with the DESI survey of cosmic growth of structure, and determine if it is consistent with the inverted or normal mass hierarchy.
- Begin data taking with the full CMB-S4 experiment and find evidence for inflation.
- Develop prototypes and instrumentation for future experiments to refine discoveries or to continue the hunt for new particles and interactions, dark matter, dark energy, and inflation.
- Integrate results from the LHC, DUNE, dark matter, dark energy, and CMB experiments into a new theoretical framework.

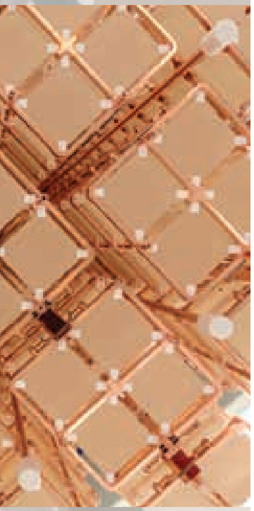


Left: Nicole Apadula and students Berenice Garcia and Fernando Torales Acosta assemble and test components for the ALICE Inner Tracking System (ITS) silicon pixel detector upgrade.

Middle: Three-dimensional reconstruction of radiation from a localized Co-60 source. Gamma rays from the source were detected by a multi-sensor radiation-detection system mounted on an unmanned aerial system (UAS) flown around a three-story concrete building.

Right: Towers of tellurium dioxide bolometric detectors used in the CUORE neutrinoless double-beta decay experiment. These detectors are cooled down to nearly absolute zero temperature and operate in the coldest cubic meter in the universe.

Background image: The GRETINA detector, designed, built, and first used at Berkeley Lab, also serves as the starting point for GRETA, the full-volume or “4π” Gamma Ray Energy Tracking Array, to be installed at the Facility for Rare Isotope Beams.



NUCLEAR SCIENCE

VISION

The physics of nuclei is fundamental to understanding the universe, and is also very much a part of our lives.

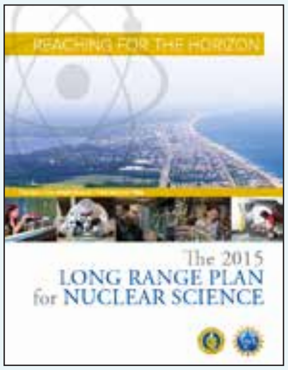
MISSION

To study the atomic nucleus for the advancement of fundamental science and to use that science for the betterment of society. This is accomplished through the development of advanced instrumentation, which is used at state-of-the-art accelerators and facilities, and of new ideas, taking advantage of novel theoretical approaches and computational methods.

INTRODUCTION

Nuclear Science at Lawrence Berkeley National Laboratory (Berkeley Lab) has a broad portfolio that spans all major thrusts of the field, and the Lab's strategy is strongly aligned with the national vision articulated in the 2015 Nuclear Science Advisory Committee (NSAC) Long Range Plan. In the following pages there is a short description of each of the major Programs in Nuclear Science at the Lab: Nuclear Structure, Neutrino Properties, Relativistic Nuclear Collisions, Theory and Computation, and Applied Nuclear Physics. The current status and future plans are detailed for each Program, including the short- (roughly five-year) and long-term (over the next decade) time frames. In addition, there is a section discussing the 88-Inch Cyclotron facility, which is a dedicated low-energy ion accelerator used for both basic science research and a variety of Nuclear Data and Space Effects Testing applications.

NSAC LONG RANGE PLAN



The exploration of nuclear science has been guided by a series of long-range plans prepared by NSAC at the request of the Department of Energy (DOE) Office of Science and the National Science Foundation (NSF) Directorate of Mathematical and Physical Sciences.

The latest plan, entitled *Reaching for the Horizon*, identifies opportunities for advancing our understanding of the science and using that science in the service of society. The plan provides a framework for the coordinated advancement of the nation's nuclear science program over the next decade.

NUCLEAR STRUCTURE

5-YEAR GOALS

- Measure fundamental properties of superheavy nuclei using the BGS and FIONA at the 88-Inch Cyclotron.
- Investigate the structure and novel properties of weakly bound nuclei.
- Lead construction of the Gamma-Ray Energy Tracking Array (GRETA) – complete Phase 1 for delivery to FRIB.

10-YEAR GOALS

- Complete full GRETA forexperiments at FRIB.

Atomic nuclei comprise 99.9 percent of the mass of the visible universe, and their properties determine many facets of the world around us, including the origin of the elements found on Earth and the processes that fuel the stars. Berkeley Lab has a vibrant program studying nuclear structure, with a focus on the structure of exotic nuclei, especially those with the largest neutron excess or the heaviest masses. Much of the research is aimed toward addressing the seemingly simple issue of the limits of nuclear existence phrased in the question, "Which combinations of protons and neutrons can combine to form a bound nucleus?"

Studying the properties of excited states in neutron-rich nuclei can reveal a great deal about their structure and the forces between the nucleons that govern the behavior. A widely used technique for studying excited states in nuclei is gamma-ray spectroscopy. Berkeley Lab scientists led the construction of one of the world's most advanced gamma-ray detector arrays, GRETINA, which uses the new technology of gamma-ray energy tracking developed at the Lab. GRETINA completed yearlong campaigns at Michigan State University (MSU) and Argonne National Laboratory, carrying out unique experiments in nuclear structure and nuclear astrophysics. The Gamma-Ray Energy Tracking Array (GRETA), the full 4π gamma-ray tracking array utilizing this technology, will be a key instrument at the future Facility for Rare Isotope Beams (FRIB) at MSU. GRETA is now under construction, with Berkeley Lab as the lead.

GRETA: Gamma-Ray Energy Tracking Array

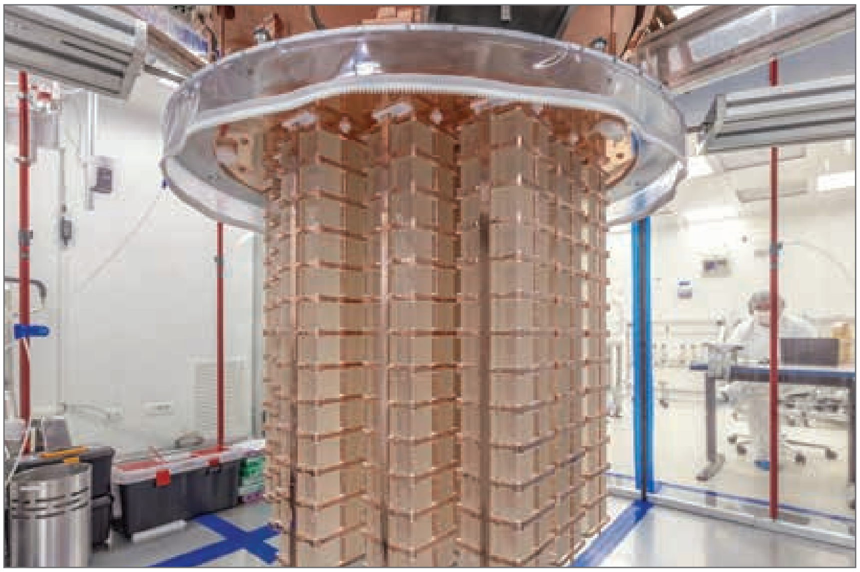
GRETA marks a major advance for γ-ray detector systems, providing order-of-magnitude gains in sensitivity compared to existing arrays. It uses highly segmented, hyper-pure germanium crystals, together with advanced signal-processing techniques, to determine the location and energy of individual γ-ray interactions. This information is then combined to reconstruct the incident γ-ray in a process called tracking. Its unique tracking capabilities make GRETA a key instrument for nuclear and nuclear astrophysics studies at the future FRIB facility.

The study of the heaviest elements by Berkeley Lab scientists dates back to the very birth of the Lab and resulted in the discovery of 14 transuranium elements. The main scientific question that drives the field, and which still evades an answer today, is, "What is the heaviest nucleus?" A unique experimental program on superheavy nuclei (SHN) continues at the 88-Inch Cyclotron (see later section). For instance, Berkeley Lab scientists recently identified gamma rays in Mc (Z=115) decay chains, which represent the first spectroscopy on SHN. SHN are created in the bombardment of targets by the beam particles, and are separated from the massive background of unreacted beam and unwanted reaction products by passing through the Berkeley Gas-filled Separator (BGS). Upgrades to the BGS, called FIONA, will enable next-generation experiments for the first direct measurements of the atomic number (Z) and mass number (A) of SHN.

NEUTRINO PROPERTIES

In the study of neutrinos, Berkeley Lab's critical role in the discovery of neutrino flavor transformation at the Sudbury Neutrino Observatory (SNO) experiment has been widely recognized. The metamorphosis of neutrinos from one type to another requires that neutrinos have mass, which has profound consequences for our understanding of elementary particles and the processes that occur in nature (see sidebar). The SNO discovery shared the Nobel Prize in Physics in 2015. Other notable results from neutrino experiments involving Berkeley Lab scientists include the first observations of geoneutrinos (in the KamLAND experiment in Japan) and ultra-high-energy cosmic neutrinos (in the IceCube experiment at the South Pole). SNO and KamLAND were also recognized in the 2016 Breakthrough Prize in Fundamental Physics.

Berkeley Lab is engaged in several of the major experiments to measure the masses and other properties of neutrinos. These experiments include the Cryogenic Underground Observatory for Rare Events (CUORE), MAJORANA DEMONSTRATOR (MJD), and SNO+. Berkeley Lab is the lead DOE laboratory for the CUORE project. The focus of these experiments is on ultralow-background measurements carried out deep underground to search for neutrinoless double-beta decay ($0\nu\beta\beta$). The observation of $0\nu\beta\beta$ would demonstrate that the



Towers of tellurium dioxide bolometric detectors before their final integration with the cryogenic system in the CUORE experiment at the Gran Sasso underground laboratory in Italy.

5-YEAR GOALS

Continue to lead the search or neutrinoless double-beta decays in the CUORE, MAJORANA DEMONSTRATOR and SNO+ experiments.

Develop cutting-edge detector technologies that are necessary for observing neutrinoless double-beta decays with a half-life longer than 10^{28} years in the next-generation experiments.

Lead the design and planning of the next-generation neutrinoless double-beta decay experiments (LEGEND and CUPID) based on the technologies developed at Berkeley Lab.

10-YEAR GOALS

Lead the construction and commissioning of a next-generation neutrinoless double-beta decay experiment that would reach a half-life limit of at least 10^{28} years.

Establish the feasibility of the technology for an experiment beyond the next-generation neutrinoless double-beta decay experiment.

Discovery of Neutrino Oscillations

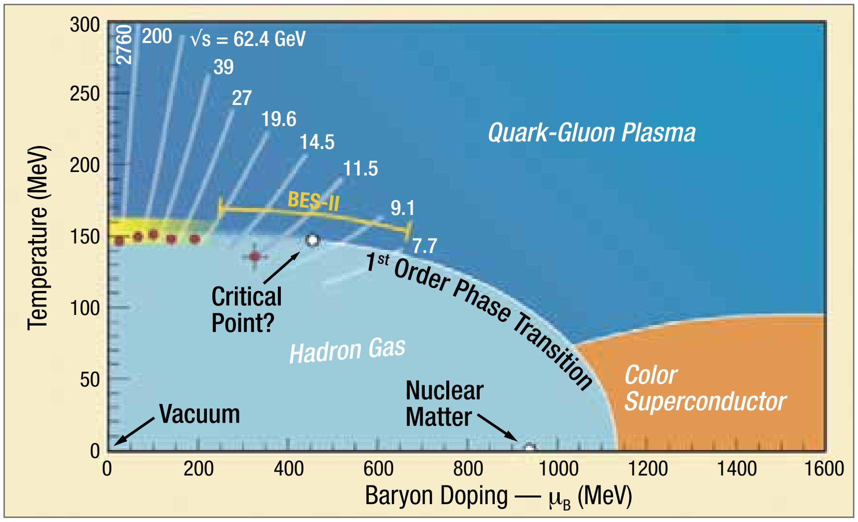
This picture shows the SNO detector, installed 6,800 feet underground at the Creighton nickel mine near Sudbury in Ontario, Canada. Berkeley Lab scientists and engineers designed and built the geodesic structure for nearly 10,000 photomultiplier tubes. On June 18, 2001, the first scientific results of SNO were published, providing the first clear evidence that neutrinos are able to transmute from one type another as they travel from the sun to the detector. The transformation implies that neutrinos have nonzero masses. The total flux of all neutrinos measured by SNO agrees well with theoretical predictions. Further measurements carried out by SNO have since confirmed and improved upon the precision of the original result.

neutrino is its own antiparticle (that is, a "Majorana" particle), provide information on the absolute neutrino mass scale, and signify that the lepton number is not conserved, with profound implications for theory and our understanding of the universe. Because of the uncertainties in experimental backgrounds and theoretical matrix elements, it is important to study multiple candidate nuclei for $0\nu\beta\beta$ experiments. Nuclear Science is pursuing experiments using ^{130}Te (CUORE and SNO+) and ^{76}Ge (MJD) that incorporate different technologies.

While current experiments can only place limits on the neutrinoless double-beta-decay half-life, the next generation of experiments has enormous potential to actually discover the process. With masses of relevant isotopes approaching the ton scale, sensitivity is likely to be improved by two orders of magnitude, enabling observation of the process if the half-life is in the range of 10^{27} to 10^{28} years. This will be, by far, the rarest process to be directly observed by scientists, and Berkeley Lab intends to be a leading player in the discovery with the new Large Enriched Germanium Experiment for Neutrinoless Double-Beta Decay (LEGEND) and the CUORE with Particle Identification (CUPID) experiments.

RELATIVISTIC NUCLEAR COLLISIONS

Berkeley Lab plays a leading role in the experimental and theoretical study of quark-gluon plasma (QGP), a state of matter occurring at very high temperature that filled the universe a few microseconds after the Big Bang. As a new state of matter, the QGP occupies one region of a nuclear phase diagram. The aim of the program is to map out and understand the different phases of nuclear matter that are encountered.



The Relativistic Nuclear Collisions program investigates the properties of quark-gluon plasma. NSD scientists lead the Beam Energy Scan (BES) program at RHIC to study the phase transition of this new state of matter under different initial conditions.

QGP experiments study collisions of heavy nuclei at extremely high energies, and are carried out with the Solenoidal Tracker (STAR) detector at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider's (LHC's) ALICE (A Large Ion Collider Experiment) detector. Lab scientists play leading roles in both of these experiments. Berkeley Lab scientists and engineers designed and constructed the main tracking detector of STAR, called the Time Projection Chamber (TPC), and Berkeley Lab led the Electromagnetic Calorimeter detector project for ALICE. Seminal measurements showed that the QGP behaves as a "perfect fluid" and flows with the lowest possible viscosity allowed by the laws of physics. Berkeley Lab's theoretical and experimental roles in discovering the quenching of high-energy "jets" (i.e., collimated sprays of particles resulting from fragmentation of energetic quarks and gluons) were pivotal; the result indicates that the QGP has unprecedentedly high density. Most recently, the Heavy Flavor

5-YEAR GOALS

Heavy Flavor Physics: Data analysis with the STAR HFT, construct the ALICE ITS Upgrade, construct the sPHENIX MVTX, and exploit their physics.

QCD Phase Diagram: Complete the STAR BES program, to search for the QCD phase boundary and the critical point. Explore physics of the high-baryon-density region.

Jet Physics: Probe QGP at various length scales at RHIC (STAR) and LHC (ALICE) through jet and jet-substructure observables.

Instrumentation: Expand the program's instrumentation capability in anticipation of future opportunities, including the EIC.

Computing: Leverage current and future HPC systems to support data processing and analysis.

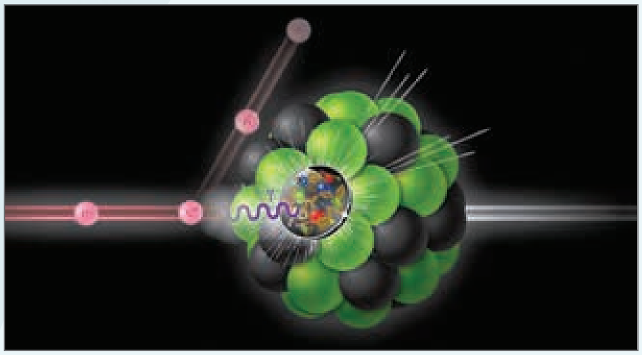
Ultra-Peripheral Collisions (UPC): Exploit UPC and diffraction with LHC data to probe the structure of heavy nuclei.

Hadron/Medium Energy Physics: Complete the hadron physics program at RHIC, engage in the parity-violation program at Jefferson Lab.

10-YEAR GOALS

Exploit the physics from data acquired with STAR HFT, sPHENIX MVTX and the ALICE ITC upgrade.

Toward EIC: Leadership in the design and construction of a future Electron-Ion Collider and its instrumentation.



The Electron-Ion Collider

At high energies and densities, nuclear matter is a teeming many-body system of quarks, antiquarks, and gluons interacting with one another via the strong force.

The EIC will enable tomography of the gluons, revealing the role they play in the origin of the nucleon spin and the generation of nuclear mass. It will also allow scientists to search for a long-predicted form of matter known as the gluon condensate. A high-energy, high-luminosity polarized EIC is the highest priority for new facility construction in the 2015 NSAC Long Range Plan. *Graphics courtesy of Brookhaven National Laboratory.*

Tracker – which was constructed at Berkeley Lab and represents the first major deployment of new Monolithic Active Pixel Sensor (MAPS) technology – showed that heavy quarks lose a large amount of their energy in the plasma, similar to the jets. The study of heavy quarks will continue using the Inner Tracker Upgrade for ALICE that is under construction, with Berkeley Lab playing a lead role. Concurrently, at RHIC, high-precision measurements of heavy quarks will be enabled by the foreseen third-generation MAPS Vertex Detector (MVTX) for the proposed sPHENIX experiment. Berkeley Lab is one of the leading institutions of the MVTX project.

To explore the nuclear phase diagram, Berkeley Lab scientists are leading a Beam Energy Scan (BES) program at RHIC that allows variation of the "chemical potential" (baryon doping) of the nuclear matter formed during a collision by changing the initial beam energy. The BES program aims to establish phase boundaries in the nuclear phase diagram and to identify the location of the critical point.

Berkeley Lab scientists will lead efforts at the proposed Electron-Ion Collider (EIC). An exploration of the role of gluons in contributing to the spin of the nucleon – which Berkeley Lab scientists are already pursuing using the unique, polarized proton beams at RHIC – and the behavior of ultradense gluon matter are of fundamental interest to physicists who will use the EIC.

Berkeley Lab led the construction of STAR's Heavy Flavor Tracker. This instrument enables, for the first time, precision tracking measurements of heavy quarks at low momentum.

THEORY AND COMPUTATION

Nuclear Theory at Berkeley Lab addresses all of the major scientific themes of the field, including the properties of hot and dense nuclear matter, the structure of nucleons and nuclei, the role of nuclei and neutrinos in astrophysics, many-body physics, and fundamental symmetries. Berkeley Lab theorists use cutting-edge theoretical techniques and methods for their research, including perturbative quantum chromodynamics (QCD), chiral perturbation theory, many-body effective theory, and high-performance computational methods.

Computational nuclear physics efforts are applied to a broad range of problems in nuclear astrophysics, lattice QCD, relativistic fluid dynamics in heavy-ion collisions, and calculations of nuclear fission. Across the world, the race is on to develop computers capable of performing more than 10^{18} floating-point operations per second – this is known as exascale computing. These high-performance computers can enable detailed simulations of neutron star mergers, for example. High-performance computing resources are also needed to better model multidimensional hydrodynamics and gravity, weak interactions and neutrino transport, the nuclear equation of state, and the detailed nuclear reaction networks.

5-YEAR GOALS

Achieve the science goals in all current topical collaborations.

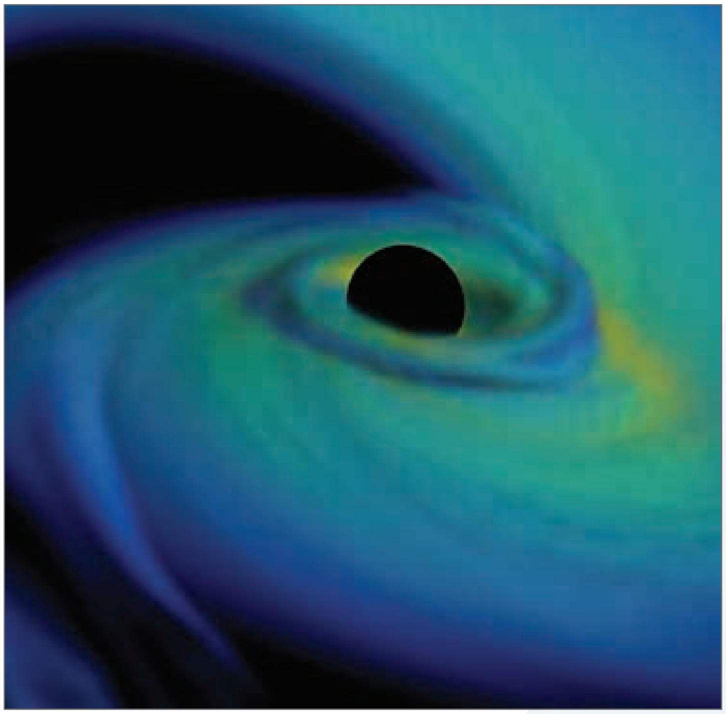
Maintain the heavy-ion program and start the EIC theory initiatives.

Strengthen nuclear many-body physics and lattice QCD.

10-YEAR GOALS

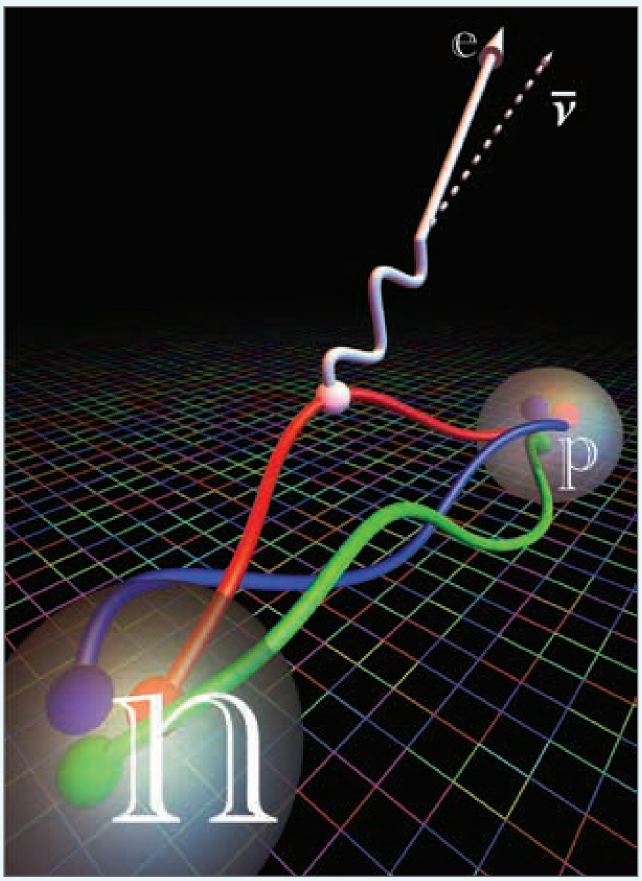
Berkeley Lab's Nuclear Theory Group to lead as one of the nation's premier theory centers on the highest-priority research goals of the field, including lattice QCD, computational physics, and nuclear astrophysics.

The Nuclear Theory effort at Berkeley Lab is strongly engaged with the experimental activities on relativistic nuclear collisions, neutrino physics including double-beta decay, and low-energy nuclear structure and reactions. Current research probes the novel partonic structure of nucleon/nucleus; supports the Beam Energy Scan experimental program at RHIC; studies hard probes of quark-gluon plasma; simulates heavy-element production in supernovae and in neutron star mergers; and performs lattice QCD calculations for neutrinoless double-beta decay and electric dipole moments (EDMs) in large nuclei, nucleons, and in nuclear structure.



A simulation of a neutron star and black hole merger.

Berkeley Lab's Nuclear Theory Group remains a premier center in the nation, focused on the highest-priority questions of the field: Is there a critical point in QCD, and how do we prove or exclude its existence? What are the properties of QGP? Will the EIC determine the orgin of the proton spin? Can we predict properties of nuclei from first-principle calculations? Can we connect the structure of nuclei near the drip line to the properties of the astrophysical sites where they are created? How do we model the evolution and the inner workings of dense astrophysical systems through the disparate signals in multi-messenger astronomy?



The axial coupling constant g_A is a fundamental parameter that plays important roles in many aspects of nuclear physics, especially in weak interactions. Future lattice QCD calculations in Nuclear Science Division will improve the precision of this constant and shed light on the discrepancy in different neutron lifetime measurements.

Progress in many research areas in low-energy nuclear physics requires a quantitative connection to QCD, the fundamental theory of nuclear strong interactions, which can only be made through a coherent effort with lattice QCD and effective theories of nuclear physics. The application of lattice QCD to nuclear physics is beset by many challenges, most notably the signal-to-noise problem, related to the notorious fermion sign problem, rendering the calculations exponentially more expensive. The Theory program at Berkeley Lab, working closely with colleagues at Lawrence Livermore National Laboratory and NVIDIA Corporation, focuses on overcoming these challenges through the design and implementation of new physics and computational algorithms.

A prime example is their recent state-of-the-art calculation of the axial coupling of the nucleon. These fundamental results from lattice QCD calculations can then form the building blocks for the computations of nuclear structure and reactions using tools such as a many-body effective theory of nuclear physics.

APPLIED NUCLEAR PHYSICS

The Applied Nuclear Physics (ANP) program at Berkeley Lab aims to develop concepts and technologies that address outstanding questions in basic and applied research, as well as national security and medical imaging. At the core are developments of new radiation detection techniques, sensor fusion, and data processing and management.

ANP's core competencies are built upon several research focus areas, ranging from contextual sensor data fusion to data management. Fusing contextual and radiation data through the development of multisensor systems and algorithms enables a new means of detection, mapping, and visualization of radioactive sources and contamination. This capability has been applied to a large range of systems, including handheld and small unmanned aerial systems, cars or SUVs, and large manned helicopters for applications including environmental mapping and decommissioning in Fukushima Prefecture (see sidebar). ANP is also pushing the limits in the operation of ultra-low-noise, high-resolution, and high-rate germanium detectors for next-generation experiments in nuclear structure physics, neutrino and dark matter science, and astrophysics in the Semiconductor Detector Laboratory.

5-YEAR GOALS

Maintain and expand the capabilities and reach of the Semiconductor Detector Laboratory.

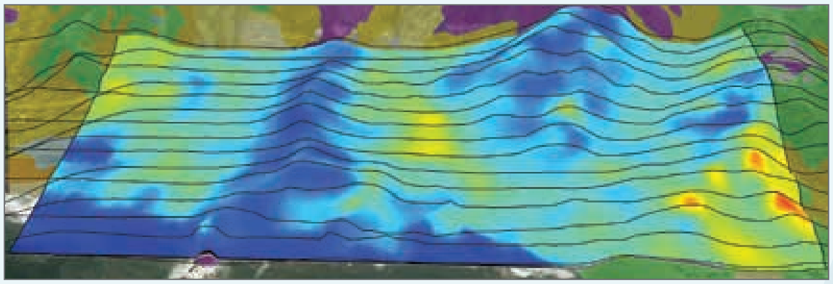
Develop research opportunities across divisions and areas.

Expand international collaborations.

10-YEAR GOALS

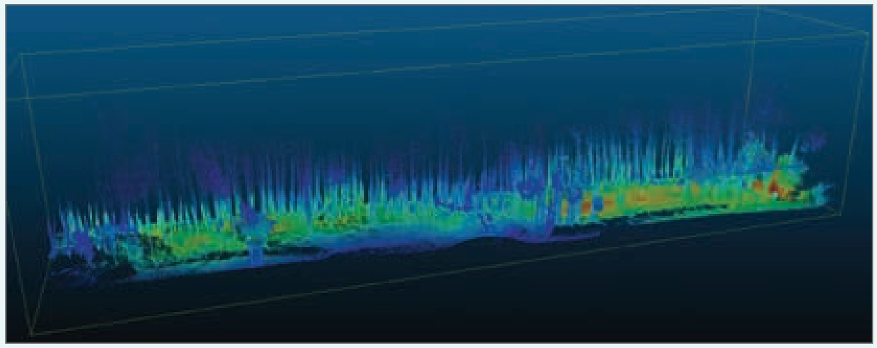
Maintain international leadership in the development of novel radiation detection and imaging concepts.

Continue to drive technological innovations at the intersection of nuclear science, engineering, and computer science.



Left: The Airborne Radiological Enhanced-sensor System (ARES) flies over the University of California, Berkeley campus during a measurement campaign to collect background radiation data spanning the San Francisco Bay Area.

Above: A result showing the reconstruction of ^{40}K activity from an ARES data collection flight over Pacifica, CA. The large variation in ^{40}K activity is the result of different geologic materials.



A 3D Cs-137 contamination map in a bamboo forest (80 meters long) obtained within 15 minutes in Fukushima Prefecture, Japan.

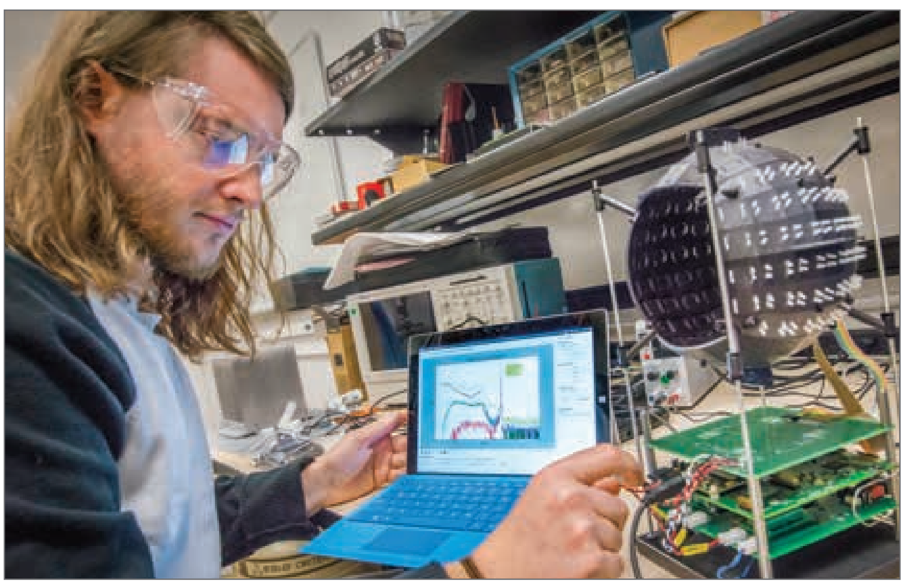
Supporting environmental management and decommissioning in Fukushima Prefecture

In collaboration with the Japan Atomic Energy Agency (JAEA), ANP researchers have successfully demonstrated real-time, 3D gamma-ray mapping of Cs-137 contamination in evacuated communities impacted by the 2011 accident at the Fukushima Dai-ichi Nuclear Power Plant. The High-Efficiency Multi-mode Imager (HEMI) and Localization and Mapping Platform (LAMP), which are gamma-ray detection systems integrated with contextual sensors, were developed by ANP and demonstrated in both handheld mode and on unmanned aerial systems. The application of this integrated technique, called scene data fusion, is a significant improvement over existing radiation-mapping capabilities and tools, enabling faster, more precise information about the location or distribution of radioactive material by visualizing the source in real time as a 3D data product (see above). Given the success of these demonstrations and measurement campaigns within the exclusion zone, ANP is now developing gamma-ray mapping technologies to be deployed in support of decommissioning and cleanup efforts at the Fukushima Dai-ichi Nuclear Power Plant.

ANP is developing innovative algorithms and frameworks to enable more robust radiation-detection capabilities, including the modeling of variable gamma-ray backgrounds; development, testing, and deployment of spectroscopic detection algorithms; and real-time, 3D gamma-ray image reconstruction. Web-based data management platforms facilitate data exploration, retrieval, online and offline analysis, and sharing across multiple DOE laboratories and contractors. For example, the Berkeley Data Cloud is being developed to facilitate dissemination of physical sensor data for initiatives such as the Multiple Informatics for Nuclear

Operations Scenarios (MINOS) Venture. ANP is also developing simulation and modeling tools such as the Urban Deployment Model as a toolset, which enables simulation, analysis, and optimization of highly distributed heterogeneous radiation detector networks in real-world environments.

In the longer term, ANP will continue to develop new concepts and technologies for a wide range of applications. These advances will address challenges at the intersection of science, engineering, new technologies, outreach, training, and engagement. New developments and innovations include new radiation detection and imaging technologies, data management approaches, and visualization tools utilizing complementary advances in machine learning and autonomous systems. This will be achieved by multidisciplinary work with domestic and international partners across multiple agencies. Opportunities exist for the establishment of a Center of Excellence that could more effectively enable the development and transition of key technologies to effect real-world changes with positive societal impact.



Ross Barnowski tests the gamma-ray imaging detector PRISM. The PRISM imager comprises discrete CdZnTe detectors arranged in a spherical configuration. It employs simultaneous Compton and coded-aperture imaging to allow a 4π field of view over an unprecedented range of gamma-ray energies.

5-YEAR GOALS

Measure fundamental properties of superheavy nuclei using the BGS and FIONA at the 88-Inch Cyclotron.

Targeted measurements for Nuclear Data and Isotopes programs.

Support national program of chip testing as recommended in a recent National Academy of Sciences report.

Construct a prototype next-generation ion source for future accelerators.

10-YEAR GOALS

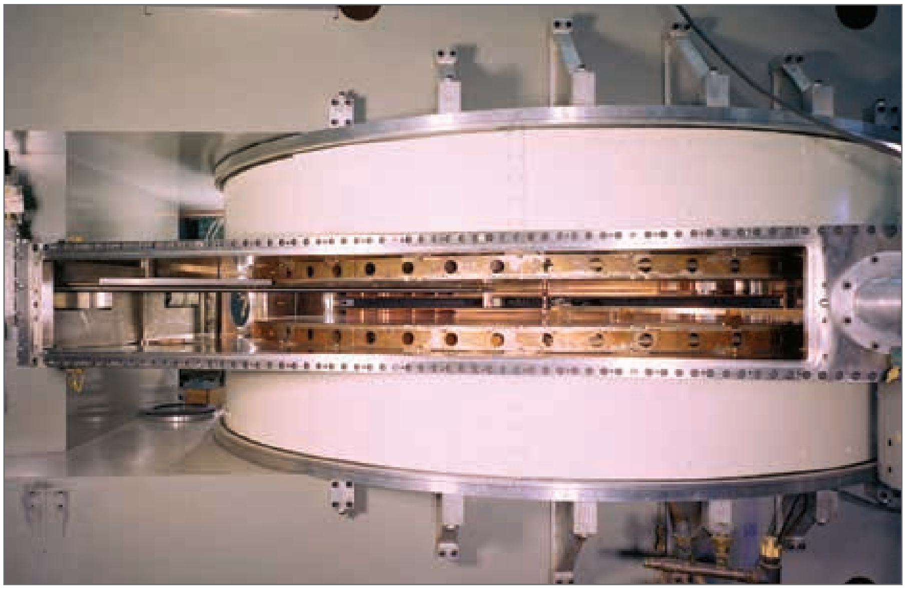
Utilize an ultrahigh-rate germanium detector array with high beam intensity for heavy-element science.

Apply a next-generation ion source concept for EIC.

Initiate a targeted program of cyclotron system improvements.

THE 88-INCH CYCLOTRON

The 88-Inch Cyclotron is a variable energy, high-current, multi-particle cyclotron capable of accelerating ions from protons to uranium. Currently, it has a dual mission of hosting a local scientific program, including the nation's leading superheavy element research effort, and also providing beams for users interested in simulating radiation space effects on electronic components. It started operation in 1961 and has maintained its position as a premier stable-beam facility through periodic upgrades, especially to its ion sources. The ion sources have enabled the acceleration of an ever-increasing variety of heavy-ion beams up to, and beyond, the Coulomb barrier.

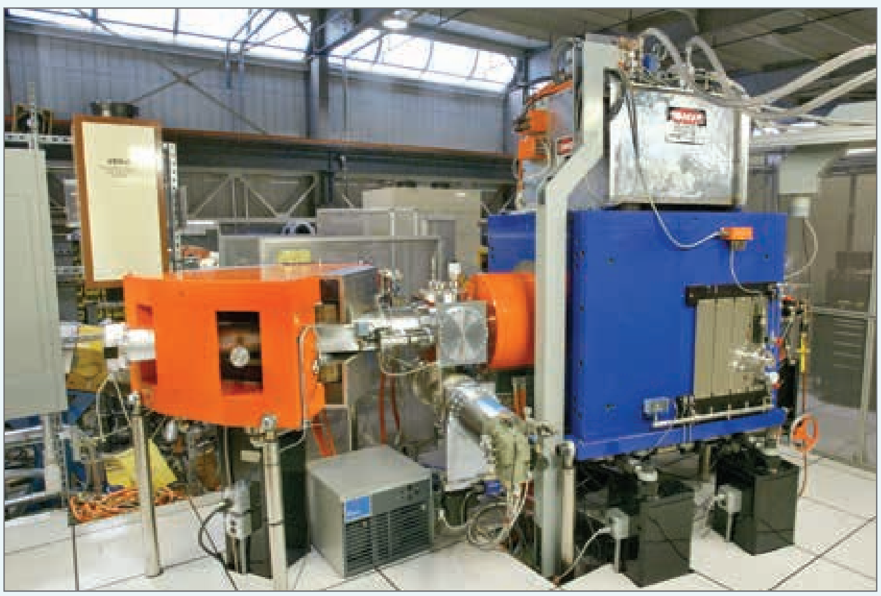


The 88-Inch Cyclotron at Berkeley Lab.

The science program at the 88-Inch Cyclotron supports the superheavy element program, nuclear structure experiments, applications in medical physics, and experiments in support of the nation's nuclear data effort. The 88-Inch Cyclotron provides intense beams of enriched isotope beams for the superheavy element research, and hosts world-class instrumentation for this research with the combination of the BGS and FIONA. With the addition of FIONA, Berkeley Lab will be uniquely positioned to perform the first charge- and mass-number identifications for superheavy elements.

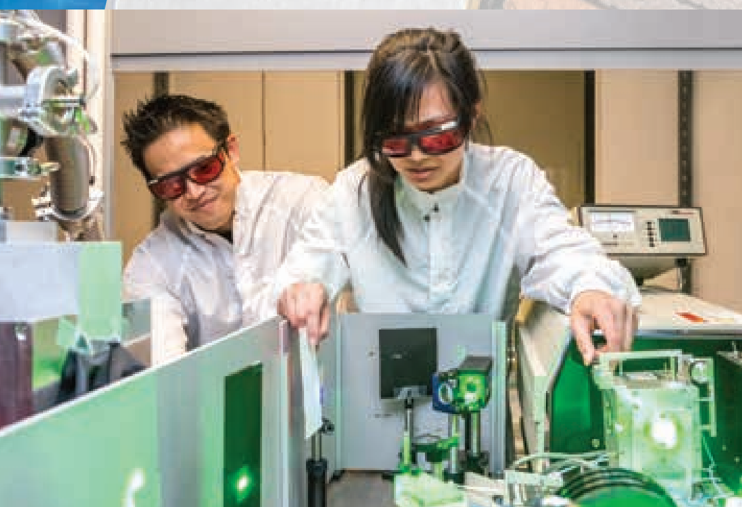
The Berkeley Accelerator Space Effects (BASE) program at the 88-Inch Cyclotron supports national security and other U.S. space programs in the area of radiation effects testing through the provision of heavy-ion cocktail beams, low-energy proton beams, and highly parallel beams with micron resolution ("microbeams"). Almost all U.S. and many foreign spacecraft and commercial aircraft launched over the past 20 years have had one or more parts tested at the 88-Inch Cyclotron BASE Facility.

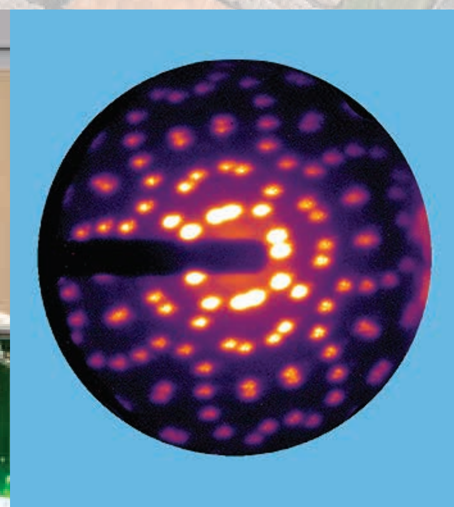
The Berkeley Lab ion source group is actively developing the next generation of electron cyclotron resonance (ECR) sources, using new superconducting materials to generate the magnetic fields necessary to control the plasma of ions and electrons. Such developments will keep the Cyclotron at the forefront of basic nuclear science and of nuclear data research for applications in medicine, nuclear energy, and national securit, and will improve the simulation of space effects for satellite components.

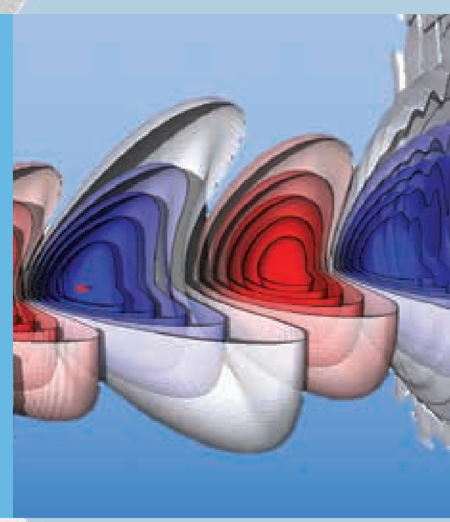


Ion Sources at Berkeley Lab

The 88-Inch Cyclotron is fed by two electron cyclotron resonance (ECR) high-charge-state ion sources, including VENUS (shown above), currently the world's most powerful ECR ion source, an evolution of which will be used for the Facility for Rare Isotope Beams (FRIB) under construction at Michigan State University. The original ECR ion source was invented by Berkeley Lab scientists and was built to enable the 88-Inch Cyclotron to accelerate beams of heavy ions.







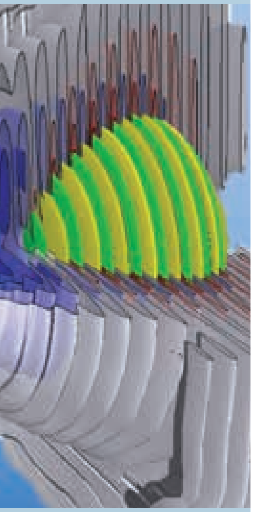
Above left: Hann-Shin Mao works with graduate student Liona Fan-Chiang at the Berkeley Lab Laser Accelerator Center (BELLA).

Center: Diffraction pattern from thin samples of gold bicrystals taken with the HiRES facility, a tool that takes ultrafast electron diffraction to new levels in order to investigate the dynamic interaction of atoms and molecules.

Right: Computer modeling of accelerator, plasma, and beam phenomena is crucial to modern accelerator design.

Background: Cross section of a superconducting magnet, a vital technology for modern accelerators and many other applications.

ACCELERATOR TECHNOLOGY AND APPLIED PHYSICS



VISION

Berkeley Lab's ATAP Division invents, develops, and deploys accelerators and photon sources to explore and control matter and energy.

MISSION

- Explore the frontiers of accelerator and photon-source science.
- Provide powerful new tools to serve the nation's needs.
- Develop the national scientific workforce and educate the next generation – students and postdoctoral researchers.

STRATEGY

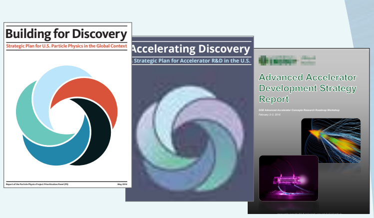
Our strategy is built upon three pillars:

Pursuing discovery science and delivering technological innovation. ATAP develops frontier accelerators and radiation sources for applications that will benefit science, security, and medicine, and lead to industrial applications.

Strengthening and renewing Berkeley Lab's facilities. Accelerator science and technology for ongoing improvements to the Advanced Light Source assures the scientific vitality of this important DOE user facility and prepares for the ALS Upgrade.

Contributing to national and international priorities in areas that capitalize on our unique expertise and capabilities. Recognized as a partner of choice for leading accelerator facilities, we are working with many of today's most exciting and challenging accelerator-related projects and developing opportunities to contribute to those of tomorrow.

A MISSION GUIDED BY VISION AND COMMUNITY



We align our strategy and proposed work with guidance such as *Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context* (the "P5 Report") and the DOE High Energy Physics Advisory Panel's *Accelerating Discovery: A Strategic Plan for Accelerator R&D in the U.S.* Influential strategic guidance in recent years has also come from the DOE's *Advanced Accelerator Development Strategy Report* and the National Academies report *Opportunities in Intense Ultrafast Lasers.* As part of this, we organize, participate in, and seek guidance from workshops, reviews, and other stakeholder venues.

Key elements of Berkeley Lab strategy – including discovery science in fundamental physics, and science with the present and upgraded Advanced Light Source – also guide the planning and execution of our work.

5–10 YEAR GOALS

Lead and execute the U.S. DOE Magnet Development Plan toward high-performance, low-cost magnets for colliders.

Develop advanced compact lattice magnetics, small-bore undulators, and superconducting undulators needed for next-generation light sources like ALS-U and FELs such as LCLS-II.

Contribute advanced magnet technology to applications such as future fusion facilities, in particular utilizing high temperature superconductors; advanced delivery systems for medical facilities; and specialized magnets for ion sources and applications.

PURSUING DISCOVERY SCIENCE AND DELIVERING TECHNOLOGICAL INNOVATION

DEVELOPING NEXT-GENERATION MAGNETS

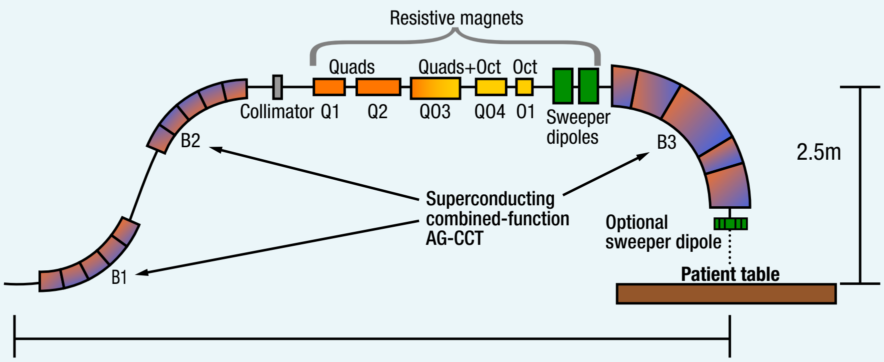
Progress in particle accelerators, and many other fields, has always gone hand in hand with the achievable strength and quality of magnets that guide the beams of charged particles. In many of today's accelerators, size and cost are crucial aspects as well.

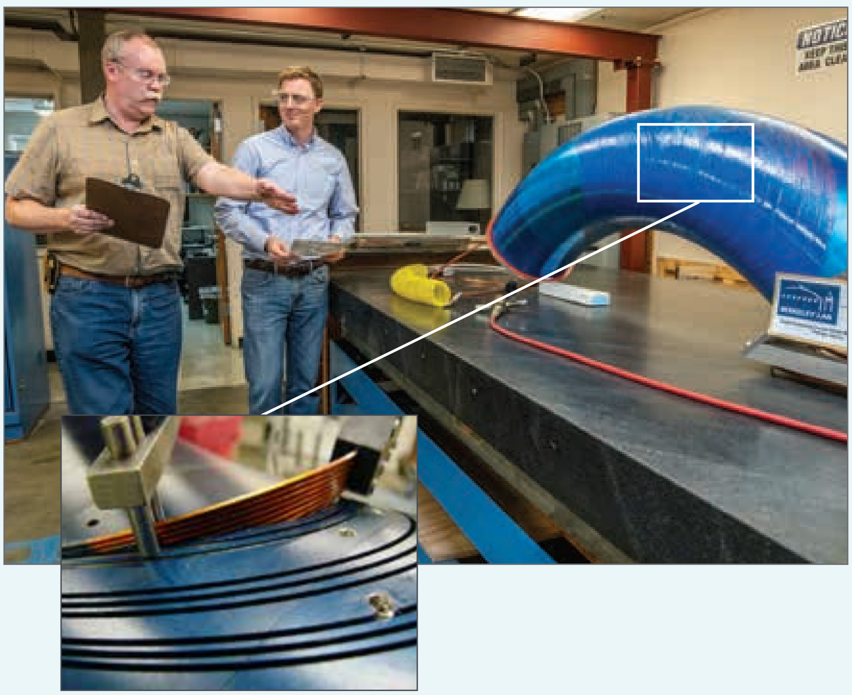
The Berkeley Center for Magnet Technology (BCMT), a program operated jointly by ATAP and the Engineering Division, offers an unparalleled set of "mesoscale to magnet" capabilities that are vertically integrated from the underlying materials science up through magnet design, fabrication, and testing.

The ATAP Division is headquarters for the multi-laboratory U.S. Magnet Development Program, a flagship DOE-OHEP effort pursuing novel magnet and conductor designs to reduce cost and increase performance for future colliders.

Facilities in the longer-term future of HEP, such as a notional Future Circular Collider, will require superconducting magnets of unprecedented cost-effectiveness as well as high performance. Beyond HEP, many Office of Science and other national needs rely on progress in magnetics; prominent examples include the next generation of light sources, such as the Linac Coherent Light Source II (LCLS-II) and the ALS Upgrade (ALS-U). Many other fields of research and applications (medical treatment accelerators, for example, and new fusion energy concepts) can also leverage this investment.

Ian Pong works with a machine that makes Rutherford-style cables out of many strands of superconducting wire. Cabling is crucial to magnet performance and a longtime strength of Berkeley Lab's superconducting magnet program. The unique and versatile machine was first developed for the Superconducting Super Collider project and since updated with many state-of-the-art quality assurance features designed to address DOE 413.3b project needs. Inset: Strands of superconducting wire enter the rollers of the cabling machine, where final cable compaction occurs.





Canted Cosine-Theta magnet geometry is a key aspect of a project with Paul Scherrer Institute and Varian Medical Systems that could greatly improve the beam delivery systems at proton and heavy ion therapy centers. Jim Swanson (l.) and Lucas Brouwer discuss the design of a superconducting canted cosine-theta (CCT) dipole magnet. Use of superconducting magnets greatly reduces the size and weight of a beam-delivery "gantry." CCT is a winding geometry with potential advantages that have attracted renewed interest for many aspects of our work in recent years. The large aperture and special optics of the gantry CCT magnet allow a range of beam energies to be handled without needing to change the magnetic field.

Detailed strategic frameworks for both BCMT and the USMDP have been published.The *BCMT Strategic Framework* describes the cross-divisional Berkeley Center for Magnet Technology (BCMT), which serves Berkeley Lab and the larger DOE community as a full-spectrum resource for both R&D and schedule- and cost-driven, project-oriented production of advanced magnet systems of all kinds.

The *U.S. Magnet Development Program Plan* lays out the charter, organization, division of effort, and overall goals for this Berkeley Lab-coordinated multi-institutional partnership. As an HEP-funded program, the primary focus is on magnets for accelerators, but the generic approach will develop magnet technologies that can be applied to a large variety of applications across the DOE Office of Science and beyond.

5–10 YEAR GOALS

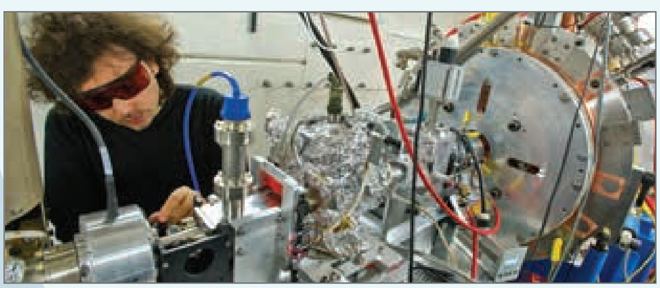
- High brightness electron sources
- Enhance the capabilities of X-ray light sources by developing:
  - Advanced injector systems.
  - Generation of ultralow-emittance beams.
  - Start-to-end modeling of accelerator and photon production systems.
- Ultrafast Electron Scattering instrumentation
  - Develop ultrafast nanodiffraction techniques.
  - Achieve time-resolved single-shot microscopy with sub-nanometer resolution.
  - Explore multimodal characterization.

ACCELERATOR SCIENCE AND TECHNOLOGY FOR THE NEXT GENERATION OF LIGHT SOURCES

X-ray light sources are highly productive scientific tools with broad applications in science and technology, and are poised for exciting advancement. Cutting-edge sources depend on high-brightness electron beams, as well as advanced magnetic insertion devices, for their high-brightness photon beams. We are developing technologies to produce and control the high-brightness beams needed for next-generation light sources, whether based on storage rings, like ALS-U, or on linear accelerators, like LCLS-II, the free-electron laser (FEL) based light source at SLAC National Accelerator Laboratory (SLAC).

FELs with MHz-class repetition rates, inverse Compton scattering sources, and ultrafast electron diffraction and microscopy instruments require new high-repetition-rate electron gun technology capable of generating high brightness beams. The Very High Frequency (VHF) gun, a new-concept radiofrequency (RF) photoinjector based on 186 MHz room temperature continuous wave technology, was built at Berkeley Lab to drive LCLS-II. The gun is based on the prototype developed in the framework of the Advanced Photoelectron Experiment (APEX) injector.

The recently approved upgrade of LCLS-II for higher energies, LCLS-II HE, would benefit from further increasing the electron beam brightness, as would ultrafast electron diffraction and microscopy applications. The APEX-II project, which aims at higher beam brightness while maintaining the operational functionality and reliability demonstrated by the present gun, is now underway.



Daniele Filippetto works with source technology that generates femtosecond-long electron bunches at relativistic energies, an ideal combination for "pump-probe" structural dynamics experiments. Combined with its MHz repetition rate, these attributes enable a world-unique beamline for ultrafast dynamics studies at the nanoscale. Researchers will be able to study complex phenomena, such as the emergence of quantum properties in the macroscopic world, and the chemical pathways by which molecular bonds are formed in chemical reactions.

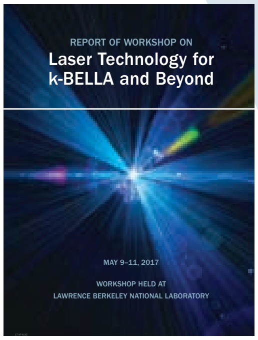
ADVANCING THE STATE OF THE ART IN ULTRAFAST ELECTRON DIFFRACTION

Researchers hope to take snapshots of atoms in motion to understand the basic mechanisms behind complex physical, chemical and biological functions. Building upon our work on electron sources, HiRES, the High Repetition-rate Electron Scattering beamline, provides a unique tool for addressing unresolved fundamental questions about the dynamical behavior of interacting atoms and molecules.

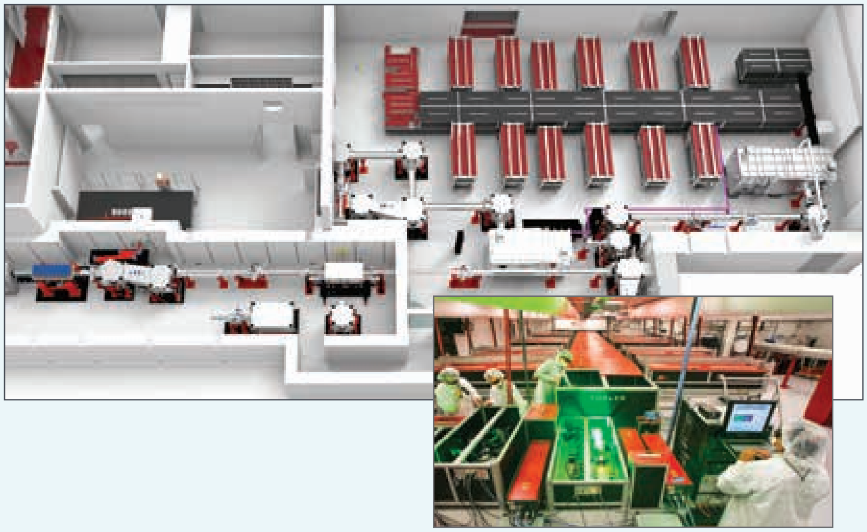
ULTRA-COMPACT ACCELERATORS AND RADIATION SOURCES FOR SCIENCE, SECURITY AND MEDICAL APPLICATIONS: BELLA, BELLA-i AND k-BELLA

Laser-plasma accelerators can produce electric field gradients (with which particles are accelerated) more than 100 times higher than conventional accelerators. This holds the promise of making accelerators far smaller and cheaper. The Berkeley Lab Laser Accelerator Center (BELLA) is the world-leading program in the development of laser-plasma electron accelerators.

Laser-plasma acceleration addresses a national need (as outlined in the P5 Report) to develop compact, high-field accelerators. Spinoffs along the path to the long-term goal of an HEP collider hold promise for many related fields. These include ion accelerators for researching the biophysics foundations of next-generation medical treatment, as well as high-energy-density physics; LPA-driven FELs for ultrafast science; monoenergetic sources of MeV photons for nonproliferation and for nondestructive test; and many other examples of "bringing the accelerator to the application" in research and industry.



A workshop, held at Berkeley Lab May 9–11, 2017, covered near- and long-term technology prospects for ultrafast lasers that could operate in the multi-kW to even tens-of-kW average power range. Such laser performance is needed for k-BELLA, which will be our next-step user facility; further stepping stones to a laser-plasma accelerator relevant to high-energy physics; and spinoff benefits *en route*.



BELLA's 5-year goals require capabilities and infrastructure investments that include the construction of a second short-pulse laser beam line with the ability to switch between long- and short-focal-length focusing to complement our current long-focal-length capability. A broad range of of exciting experiments will be enabled. In addition, implementation of a dedicated betatron beamline to provide a synchronized hard X-ray pulse will enable backlighting experiments for high energy density science and biological imaging.

5–10 YEAR GOALS

High energy physics:

- 10 GeV electron beams from a single LPA module.
- Staging of two LPA modules at the 5+5 GeV level.
- Non-linear QED experiments in new regimes.

Particle and radiation sources:

- MeV photons with an LPA using laser backscatter.
- Coherent extreme-ultraviolet beams from an LPA-based FEL.

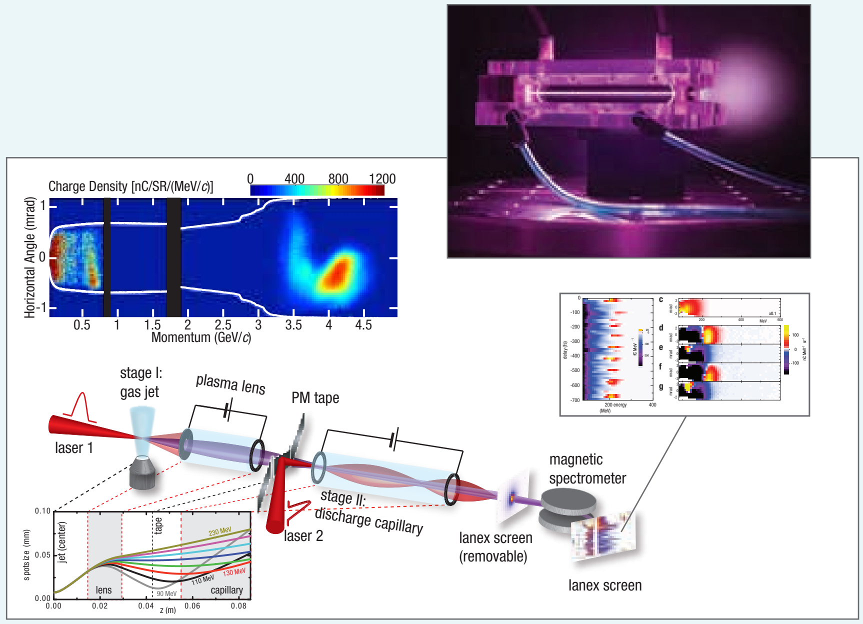
Hadron beams:

- 10-100 MeV ions from intense laser-matter interactions.

Low energy electron beams

Laser technology:

- Design, construction and operation of a user facility driven by a multi-kW laser system (k-BELLA).



Having already accelerated electrons to 4.2 GeV in a single stage (inset), and demonstrated "staging" or linkage of multiple accelerating stages powered by separate, synchronized lasers, BELLA is now in a campaign toward 10 GeV and beyond. Staging is a key element in the long-term future of laser-plasma accelerators, with advantages that include higher accelerating gradients (and therefore more-tractable length) and reasonable laser pulse energies.

Lasers are tools of discovery science as well as infrastructure for applications. States of high energy density can be formed with the high-power, short-pulse BELLA petawatt (PW) laser. Operating at 1 Hz, it enables fundamental plasma science with experimental throughput and data rates that are orders of magnitude better than those of earlier PW laser systems. Untested aspects of quantum electrodynamics are in the verge of being explored; such ultra-intense lasers can probe the nature of the vacuum itself.

Cameron Geddes (center), postdoctoral researchers Hai-En Tsai (right), and Tobias Ostermayr (near left), with a visiting student (far left), observe as plasma produced by the new Hundred Terawatt Thomson-scattering (HTT) laser at BELLA Center creates a radial rainbow when the initially almost invisible (infrared) laser pulse is frequency shifted as it ionizes air in the chamber. This shows that the laser is compressed to a short pulse duration on target. The laser is now starting experiments to enable a compact, nearly monoenergetic source of mega-electron-volt photons.

ACCELERATOR CONTROLS AND INSTRUMENTATION AND NOVEL LASER TECHNOLOGY

With the ever-increasing demands on the performance of existing and proposed accelerators, accelerator controls and instrumentation (AC&I) becomes more challenging. To meet these needs, the Berkeley Accelerator Controls and Instrumentation (BACI) Program has been formed to provide RF designs for advanced accelerators as well as beam orbit feedback systems and high performance controls for accelerator subsystems.

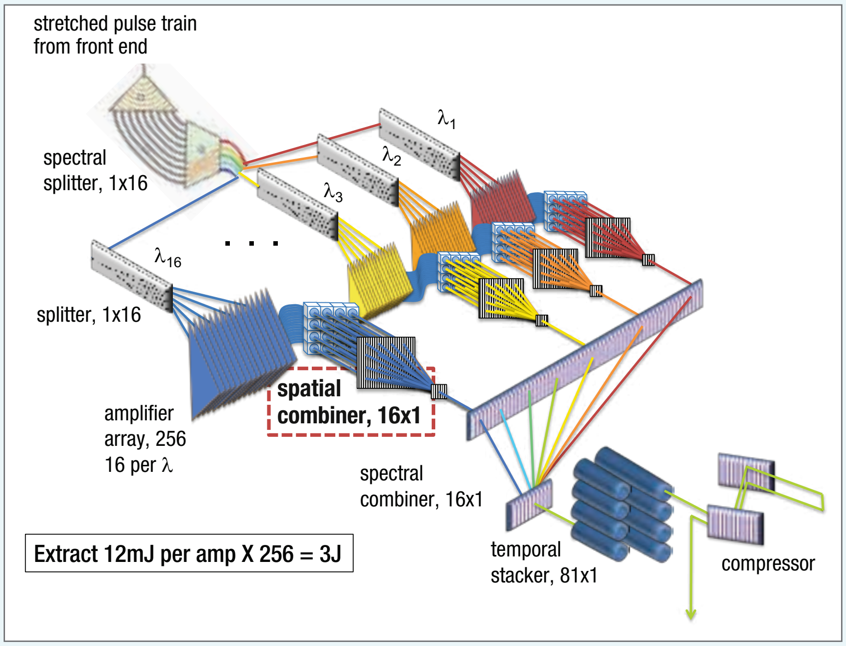
At the frontier of AC&I we are learning to take advantage of new opportunities opened up by plasma science and photonics in order to meet the demands of new acceleration paradigms and next-generation machines.

Building upon the successful delivery of the Radio-Frequency-Quadrupole (RFQ) accelerator for the Proton Improvement Plan-II (PIP-II) injector at FNAL, BACI will continue the collaboration for the Booster Upgrade and PIP-II accelerator complex.

Exploiting the tremendous progress that has been made in scientific computation, we are implementing advanced algorithms in RF device design and low-level RF (LLRF) control for particle accelerators. Our work serves the beam-quality needs of accelerator users throughout the Office of Science while advancing the AC&I state of the art.

5–10 YEAR GOALS

- Enable plasma and photonics technologies for next-generation accelerators.
- Develop concepts for high peak and average (30 kW) power in short-pulse lasers.
- Develop advanced RF controls for PIP- II accelerator complex.
- Design a next-generation low emittance high repetition rate normal conducting injector for FEL applications; (APEX-II).
- Provide state of the art qubit controls for quantum computation.



Ultrafast lasers delivering multi-kW to even tens-of-kW average power will be needed for k-BELLA. One possibility is being explored here at Berkeley Lab. Jointly with researchers at the University of Michigan and Lawrence Livermore National Laboratory, we are developing concepts for a multi-kW, short-pulse, high-peak-power laser system. Coherent spatial, temporal, and spectral combining of beams from laser fibers is one potential path to these powerful, short-pulse lasers that will be needed by k-BELLA and other future facilities.

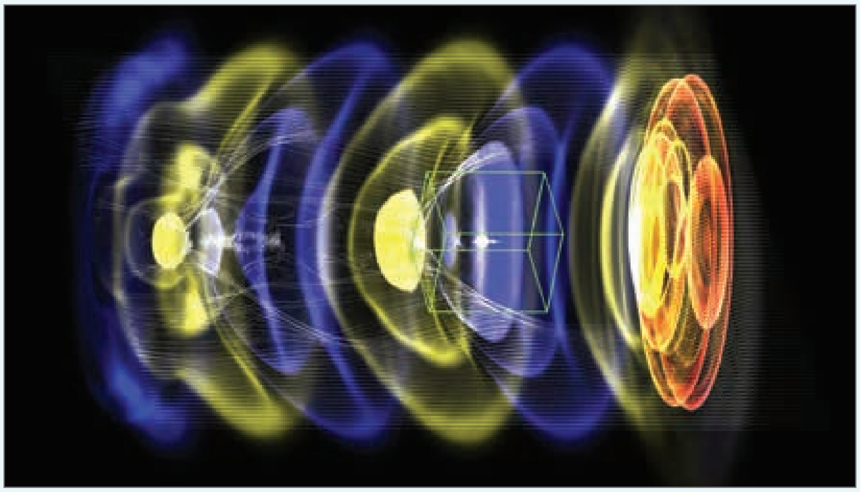
5–10 YEAR GOALS

Our overarching goal is the grand challenge of accelerator modeling, which is developing "virtual accelerator" tools that have:

- The power required for start-to-end simulation of entire particle accelerators and design aided by advanced machine learning algorithms.
- The multiphysics capability necessary for realistic virtual prototyping of complex systems.
- The speed needed for near-realtime modeling and, ultimately, realtime feedback and auto-tuning.

HIGH PERFORMANCE COMPUTATIONAL TOOLS FOR ACCELERATOR MODELING

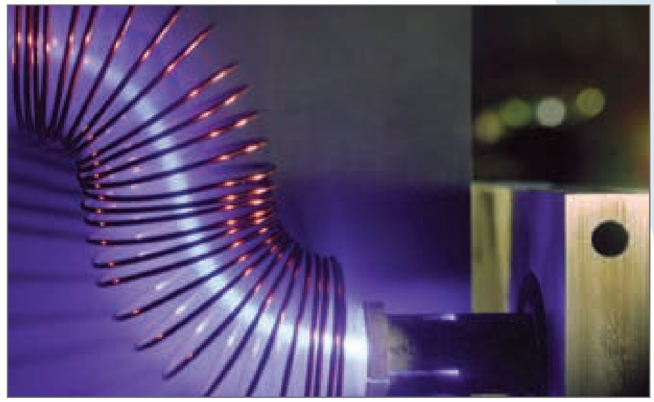
The complexity of new high-performance accelerator facilities demands the most advanced computing tools to allow high-fidelity, high-speed modeling. Advanced modeling allows users to optimize performance, identify problems and ways to circumvent or mitigate them, and even make discoveries. ATAP's Accelerator Modeling Program is based on collaboration among physicists, applied mathematicians, and computer scientists with deep knowledge in their individual domains. It manages and provides the Berkeley Lab Accelerator Simulation Toolkit (BLAST), a set of advanced codes for the modeling of particle accelerators. AMP has leadership roles in trans-institutional efforts such as DOE's Exascale Computing Project and the Consortium for Advanced Modeling of Particle Accelerators. AMP expertise is recognized and used worldwide, and the results benefit a wide variety of fields extending across much of the DOE Office of Science research portfolio.



Snapshot from a WarpX 3D simulation of a laser-driven plasma accelerator. The laser (red) propagates from left to right and creates a plasma wake (yellow and blue) that accelerates a small electron beam (white) to high energy. A mesh refinement patch (green box) is used to increase the resolution and accuracy around the electron beam. ATAP's Accelerator Modeling Program is leading the application team working on "Exascale Modeling of Advanced Particle Accelerators," which is developing a novel accelerator simulation code (program). The new code will combine the latest and most powerful algorithmic advances (such as mesh refinement for zooming on small-scale effects) and harness the power of future exascale supercomputers for the exploration of outstanding questions in the physics of acceleration and transport of particle beams in chains of plasma accelerators.

PLASMA SCIENCE FOR ACCELERATORS AND APPLICATIONS

Building upon long experience in ion source and beam control technologies, ATAP is noted for applications of plasmas, cathodic arcs, and low-power ion beams. Research facilities and a wide variety of industrial applications have enjoyed the benefits of cooperative R&D, and innovations have been recognized with 18 R&D 100 awards. New coatings for accelerator and laser applications are now being developed.



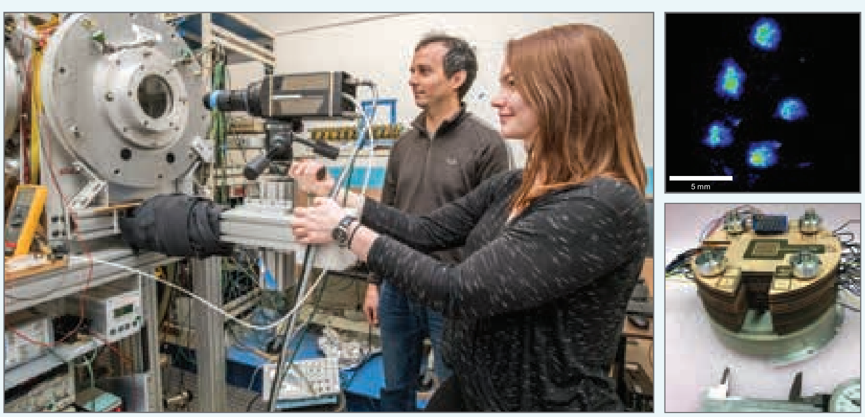
A magnetic filter conveys plasma to a surface being coated while allowing undesirable macroparticles to pass straight through; it was part of an R&D 100 winning product in collaboration with a private sector company.

MEMS BASED ION ACCELERATORS

Ion beams are widely used in research and industry, but for many applications the cost or size of ion accelerators is limiting. A leading theme across ATAP is enabling disruptive advances, such as scaling down the size and cost of accelerators. We have developed a novel accelerator architecture based on stacks of wafers. The wafers are fabricated using low-cost micro-electromechanical systems (MEMS) techniques in a collaboration with Cornell University. This approach could enable massive scaling and implementation of compact, low-cost RF accelerators in areas such as ion implantation, mass spectrometry and plasma science.

5–10 YEAR GOALS

Advance our basic understanding of plasma dynamics to drive the development and application of plasma-based tools for advanced manufacturing, applications in accelerator development, and other high societal impact applications.



A multi-beam ion accelerator, formed from stacks of wafers structured using MEMS techniques, could provide transformational benefits in certain applications. Compared to conventional accelerators, it is compact, inexpensive, and readily scalable to larger numbers of beams for more total current or broader coverage. Here Arun Persaud mentors student Grace Woods as she takes data on its multibeam output.

5–10 YEAR GOALS

Major upgrade of instrumentation and diagnostic systems, extending ongoing upgrade campaign of last several years, will provide new state-of-the-art controls and diagnostics capabilities to the ALS.

Upgrades to linac RF and timing systems will increase performance and reliability and will continue on to serve ALS-U.

Novel undulator designs will improve ALS performance, enable ALS-U potential.

Complete design and build ALS-U. Install the new storage ring, an accumulator, and new beamlines during a year-long shutdown, followed by commissioning of the accelerators and beamlines, and the restart of user operation.

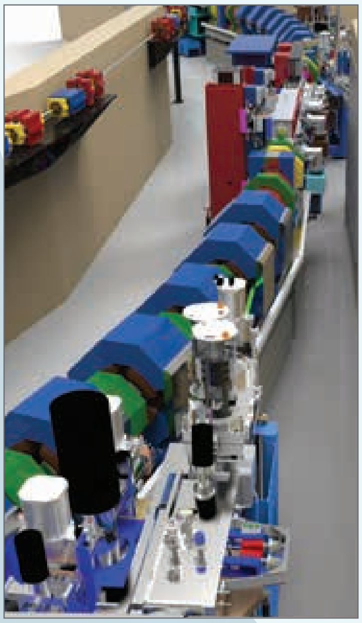
STRENGTHENING AND RENEWING BERKELEY LAB'S FACILITIES

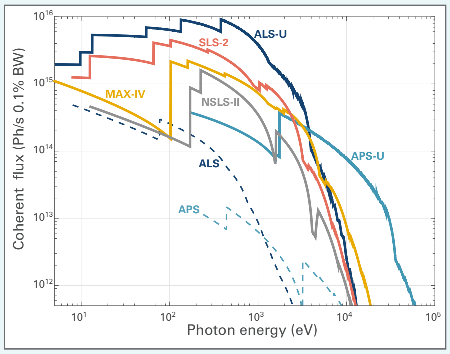
ADVANCED LIGHT SOURCE PROGRAM

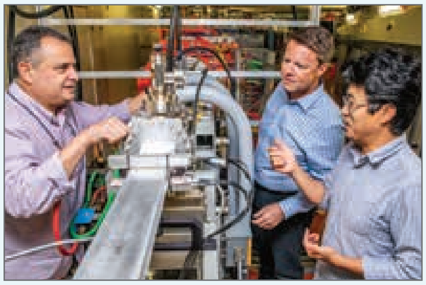
During the past 25 years, the ALS has led the world in soft X-ray capabilities, serving the core of the DOE-BES mission in this range of photon energies. These past and ongoing advances in ALS science capabilities have been enabled by a program of accelerator improvements and upgrades for better performance and reliability.

ALS UPGRADE: PREPARING FOR ANOTHER GENERATION AT THE STATE OF THE ART

A major ALS Upgrade was awarded Critical Decision Zero (CD-0) by DOE in September 2016. With an ultrahigh brightness multibend achromat storage ring replacing the existing ALS ring, ALS-U will provide diffraction-limited X-ray beams with orders of magnitude higher brightness and coherent flux. These capabilities will enable many experiments that are presently impossible. We look forward to the opportunity to proceed through conceptual design and then construction so that this major DOE user facility can enable forefront discovery science for decades to come.







In the ALS Upgrade, an arrangement of magnets called the multi-bend achromat will replace the triple-bend achromat of the existing ALS. The multi-bend achromat, pioneered at MAX IV in Sweden, is now widely used in the plans for new and upgraded state-of-the-art synchrotron radiation facilities. The combined result of this and several other changes will produce output that is orders of magnitude higher than that of the current ALS and well beyond the coherent soft X-ray flux of any storage-ring-based light source operating, under construction, or planned. Above right, l-r: Fernando Sannibale, Simon Leemann, and Changchun Sun discuss ALS-U injection.

CONTRIBUTING TO NATIONAL AND INTERNATIONAL PRIORITIES BEYOND BERKELEY LAB

Many of today's most important accelerator-based facilities for discovery science are multi-institutional and even international. Through decades of collaboration in these team-science-writ-large projects (examples include SNS, RHIC, LHC, ITER, FRIB, PEP-II, LCLS, PIP-II, and now LCLS-II), ATAP has come to be a partner of choice for the most demanding facilities worldwide. Many of these endeavors have involved close interaction with the private sector.

LCLS II AND OTHER FREE ELECTRON LASER PROJECTS

Berkeley Lab contributions are crucial to LCLS-II, an FEL facility being built at SLAC by a collaboration of five national labs and Cornell University. We are responsible for the design, prototyping, production, and tuning of the electron source (injector) and the photon sources (undulators). Berkeley Lab scientists and engineers also have critical roles as technical leads for design of LLRF controls, accelerator physics design and optimization, support for cryosystems, and other project management activities.

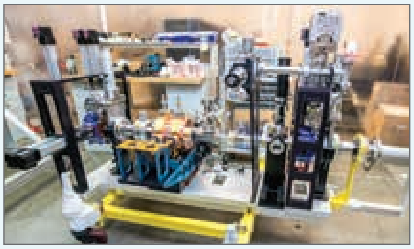
Both the soft-X-ray (SXR) and the hard X-ray (HXR) beamlines take advantage of Berkeley Lab's long-standing expertise in variable-gap hybrid-permanent magnet undulators. The HXR beamline uses a unique horizontal-gap vertically polarized undulator (HGVPU), developed in collaboration with Argonne National Laboratory. Both sets of undulators are in production under Berkeley Lab management.

Finally, we are contributing accelerator physics design expertise, supporting high-resolution start-to-end modeling that takes multiple aspects of physics into account; this has proven critical for cutting-edge light sources such as LCLS-II and other particle accelerators.

5–10 YEAR GOALS

Be a partner of choice in national and international accelerator projects that support the DOE mission, providing expertise in surmounting scientific and technical challenges and developing and delivering:

- Critical accelerator technologies for the success of the LCLS-II project and future FELs.
- High field quadrupole magnets for the High Luminosity LHC at CERN as part of the HL-LHC AUP project.
- Advanced magnets for a future Electron Ion Collider.
- Advanced magnet systems for the Office of Science, e.g., ECR ion sources and medical gantries.



In one of our several areas of responsibility in LCLS-II, Berkeley Lab designed, built, and delivered the high-repetition-rate source of tightly controlled electron bunches for LCLS-II. The injector source and our HiRES ultrafast electron diffraction facility have common roots in our years of R&D on advanced electron injectors for future light sources.

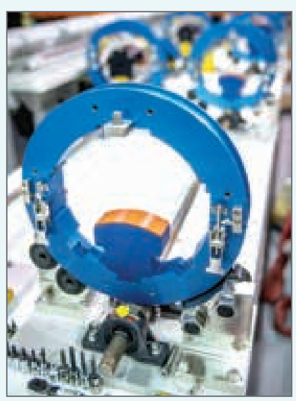
Undulators are another important area of contribution to LCLS-II. Here John Corlett examines the actuating mechanism of a soft-X-ray undulator.

HIGH-LUMINOSITY LARGE HADRON COLLIDER ACCELERATOR UPGRADE PROJECT (HL-LHC AUP)

Scientists and engineers at U.S. national laboratories lead the international community in developing the next generation of superconducting magnet technology based on Nb_3Sn superconductor. Recognizing this leadership, the DOE Office of High Energy Physics has invested in a ~13 year readiness program that resulted in ATAP participation in a major international project, the HL-LHC AUP. Berkeley Lab works closely with FNAL and BNL on the design, fabrication, and delivery of the interaction region quadrupole magnets that are crucial to this energy-frontier particle accelerator.

Berkeley Lab partners with Fermi National Accelerator Laboratory (FNAL) and Brookhaven National Laboratory (BNL) on innovative high-field quadrupoles for the HL-LHC project. *Photo by Reidar Hahn, FNAL.*

The overall upgrade, with installation beginning around 2023, is aimed at an order- of-magnitude increase in beam luminosity, with a twofold increase from these magnets alone. Higher luminosity translates into an increase in the rate of particle collisions and thus the detail with which LHC users can explore the Standard Model of Particles and Interactions and search for new physics within the LHC's energy reach. The U.S. arm of this effort, the HL-LHC AUP, received Critical Decisions 1 (approval of the decision after considering alternatives, and of the cost range) and 3a (go-ahead for procurement of long-lead-time items) from the Department of Energy in October 2017.

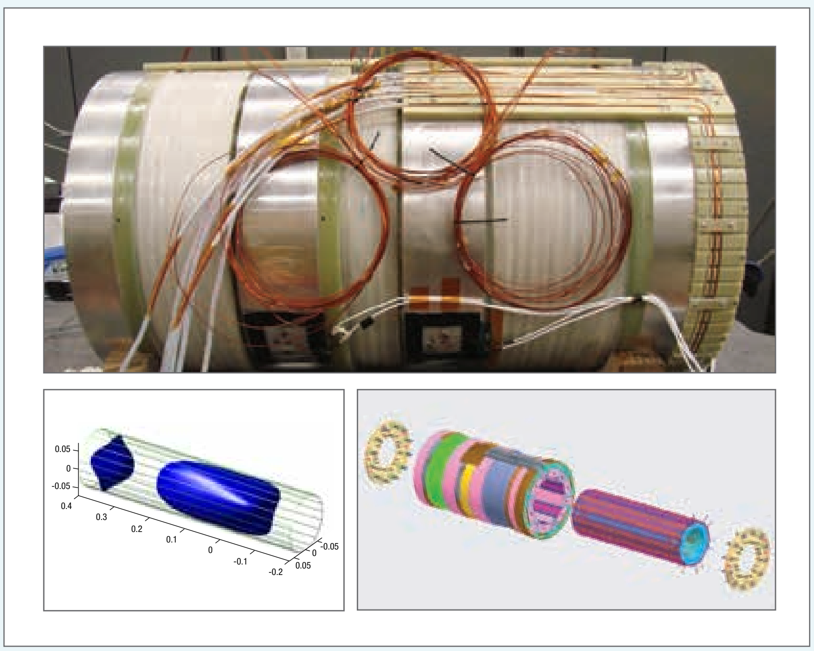


The HL-LHC requires the design, fabrication, and testing of twenty 4.2-m-long high-field superconducting quadrupoles. Andy Lin is shown adjusting the unique Berkeley Lab machine that makes the "Rutherford-style" cables used for these magnets. Berkeley lab also performs the final assembly using unique tooling devised to control the process, such as the coil rollover tools shown on the right. These magnets will be the first to use Nb_3Sn superconductor in an operating accelerator.

FRIB AND ECR MAGNETS

The Berkeley Center for Magnet Technology's expertise in superconducting magnet design, fabrication and testing has been applied to the development of a state of the art electron cyclotron resonance (ECR) magnet for the Facility for Rare Isotope Beams (FRIB) at Michigan State University, a flagship project in the DOE nuclear science portfolio. The magnet was successfully tested in October 2017 and delivered to the project in December 2017.

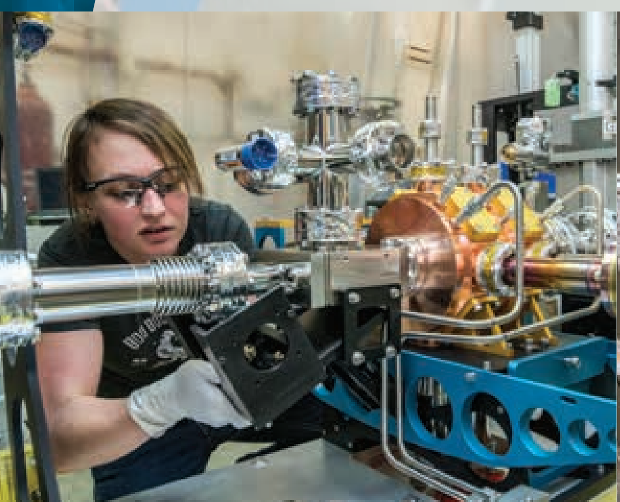
Conceptual work on the next generation of high field ECR ion sources utilizing Nb_3Sn and/or high temperature superconductors is underway. The technology can benefit FRIB and other facilities in the future.

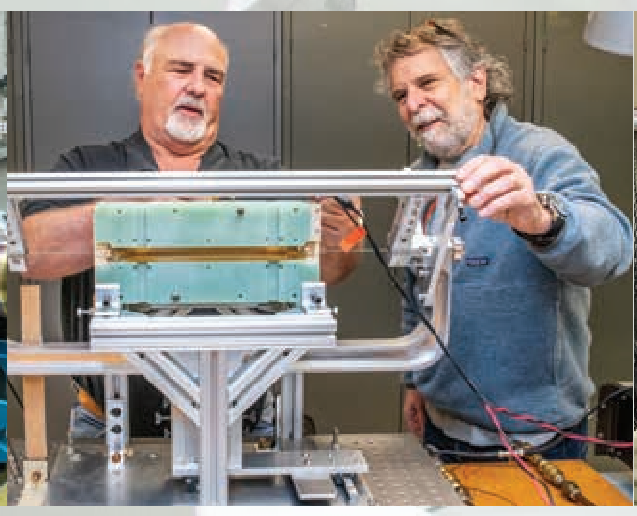


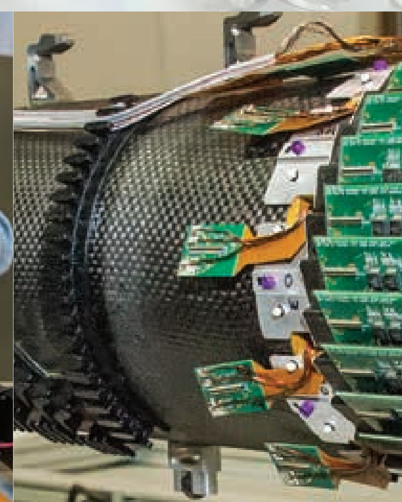
The magnet for FRIB's ECR ion source provides the combination of strong magnetic fields needed for plasma confinement in the source: a 2-tesla sextupole field in the plasma chamber with a superimposed solenoidal field profile (4 T – 0.8 T – 3 T) produced by three solenoids. The design and realization of the magnetic fields is crucial to enable confinement of the dense plasma that serves to breed the high-charge-state ions used by the accelerator.

LOOKING TOWARD AN ELECTRON-ION COLLIDER

Magnet technologies we are developing are key to higher-field fast-ramping dipoles and high-field, large-aperture interaction-region quadrupoles, areas critical for a future electron-ion collider (EIC). ATAP Division is also poised to contribute to the design of the machine through our accelerator modeling expertise.





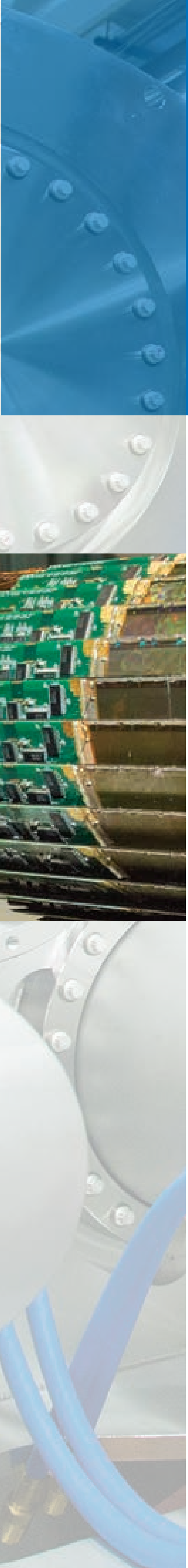


Left: Krista Williams finalizes a component assembly at Berkeley Lab for SLAC's LCLS-II injector project.

Middle: Ken Berg (left) and Chris Pappas (right) inspect the Non-Linear Kicker (NLK), which will enable top-off injection without noticeable motion of the electron beam in the Advanced Light Source-Upgrade (ALS-U).

Right: Pixel detector built at Berkeley Lab for the STAR Heavy Flavor Tracker at Brookhaven National Lab.

Background image: An ion injector exemplifies the precision and complexity demanded by state-of-the-art projects.



ENGINEERING

ADVANCING SCIENCE BY DESIGN

Since the Lab's inception, scientists, engineers and technical staff have worked closely together in conceiving, designing, and building the unique instrumentation necessary for world-class scientific research. The remarkable results of this successful collaboration are evident throughout this plan.

As the Lab grew and its programs became more diverse, it was advantageous to centralize the delivery of engineering services, hence the Engineering Division was formed. Core capabilities are maintained within the Division to support multiple programs across the Laboratory. In addition, well-trained engineering and technical staff are deployed as needed in a matrix model to operate large facilities such as the Advanced Light Source and the 88-Inch Cyclotron, and to construct complex detector projects like LZ or GRETA.

The Engineering Division delivers complete solutions for the full project cycle, from conception through design, construction, installation, commissioning, and also following the transition into operations and maintenance. Engineers and technologists are often embedded within scientific divisions, serving as key members of the science project teams.

Technical groups within Engineering engage in R&D to develop core technologies and are alert to applications beyond the original science goals. This has led to numerous successful industrial partnerships, greatly leveraging the agency investment.

STRATEGIC GOALS

- Enhance and explore rapidly evolving technologies, especially in areas where industry alternatives are not yet available; recruit and develop a talented and diverse workforce; support the Lab's mission in partnership with scientific divisions.
- Be a local and national resource for unique engineering solutions, address the nation's grand scientific challenges, and catalyze technology transfer.
- Maintain strong connections with universities to develop technology and engineering practices, and to educate the next generation of engineers.

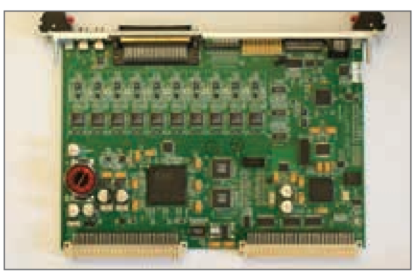
ENGINEERING DISCIPLINARY AREAS

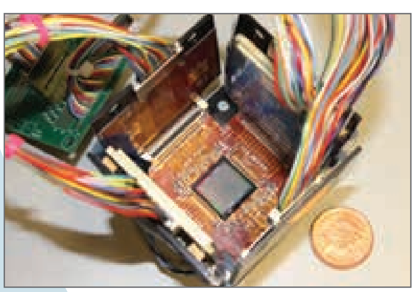
MECHANICAL

Kyle McCombs in Engineering Division's Undulator Measurement Facility (UMF) measures the magnetic field on a hard X-ray undulator for LCLS-II.

The Mechanical Engineering (ME) Department partners with scientific divisions to support projects of all sizes, providing expertise in analysis, design, fabrication and manufacturing, simulation support, and project management.

Eight engineering groups, and two manufacturing and technology groups provide the core areas of expertise that serve Berkeley Lab's needs in areas such as accelerator engineering, X-ray optics, precision (nanoscale) engineering, and large detector systems. The ME department manages projects throughout their entire life cycle by tightly integrating the process from conceptual development through requirements management, design, manufacturing, technical assembly, commissioning, and operation. Project life-cycle management includes feedback and data capture throughout.





Upper: Berkeley Lab-developed digitizer for the GRETINA detector. Lower: Novel CCD camera for low-energy X-rays, with readout electronics, is used at light sources.

ELECTRONICS, SOFTWARE, AND INSTRUMENTATION

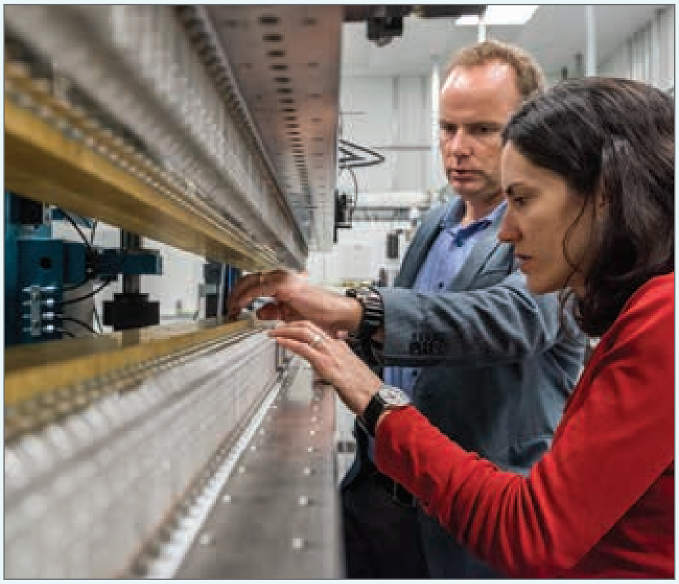
The Electronics, Software and Instrumentation Engineering Department (ESIE) deploys essential engineering expertise for projects, facilities, and research groups to enable scientific discovery.

The department comprises five engineering groups in addition to a manufacturing group and a technology group. Core expertise areas for ESIE are radiofrequency and high-voltage engineering, data acquisition, high level and low-level control systems, semiconductor detectors, integrated circuit design and data processing, electronics design for detector systems and accelerator technology, and safety and interlock systems.

MAGNETICS

Advanced, high-performance magnets are keys to many sciences, so the Engineering Division's Magnetics Department has joined with the Accelerator Technology and Applied Physics Division to form the Berkeley Center for Magnet Technology (BCMT). The center serves Berkeley Lab and the larger DOE community as a full spectrum resource for basic R&D, and for the schedule-and cost-driven, project-oriented production of advanced magnet systems.

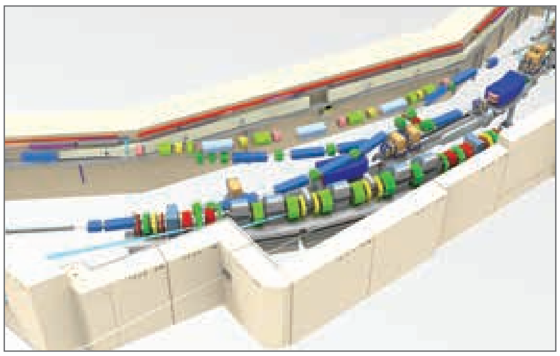
BCMT integrates accelerator physicists and magnet researchers, magnet design engineers, and fabrication teams to foster rapid progress in the development and reliable delivery of new magnet technology. BCMT aims to be partner of choice throughout the DOE complex in three program areas: magnets for light sources; superconducting accelerator magnets; and advanced concepts for magnetic materials and design. BCMT combines an internationally recognized R&D component with Engineering Division's core capabilities in magnet design, mechanical integration, fabrication, performance testing, and quality assurance.



Erik Wallén and Laura Garcia Fajardo examine an LCLS-II module in our magnetic measurement facility. Undulators call for a remarkable combination of brute strength and precision, keeping the rows of magnets precisely positioned — with adjustability measured in microns to tune the properties of the X-ray light that they cause the electron beam to emit — as they attract or repel each other with tons of force. The ability to design and build advanced undulators is a Berkeley Lab strongpoint going back to the late Dr. Klaus Halbach and the genesis of the Advanced Light Source.

CORE CAPABILITIES

ACCELERATOR SYSTEMS



A computer aided design rendering of an arc section of the proposed Advanced Light Source upgrade.

Building a modern particle accelerator calls for state-of-the-art design and implementation across a wide range of engineering disciplines. The results are tremendously important tools of discovery throughout the sciences that also have important industrial and medical applications. Berkeley Lab is a key partner in many of the most challenging accelerator projects worldwide, with contributions that include the lattice magnets that guide and focus the beam; magnetic insertion devices or undulators that produce laser-like X-ray beams out of an electron beam; radiofrequency (RF) systems; vacuum technology; fabrication, measurement and testing; and controls and instrumentation. Selected projects are highlighted in this section.

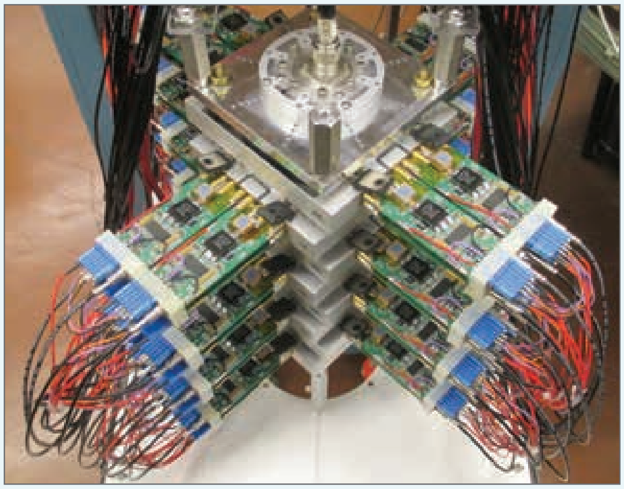
HIGH-LUMINOSITY LHC ACCELERATOR UPGRADE PROJECT (HL-LHC AUP)

CERN's Large Hadron Collider is in the midst of a project that will increase its beam luminosity by an order of magnitude. As part of DOE's arm of this effort, the HL-LHC AUP, Berkeley Lab has key roles in designing and building final-focus quadrupole magnets. This will be the first major use of a high-field Nb_3Sn superconductor in an accelerator.

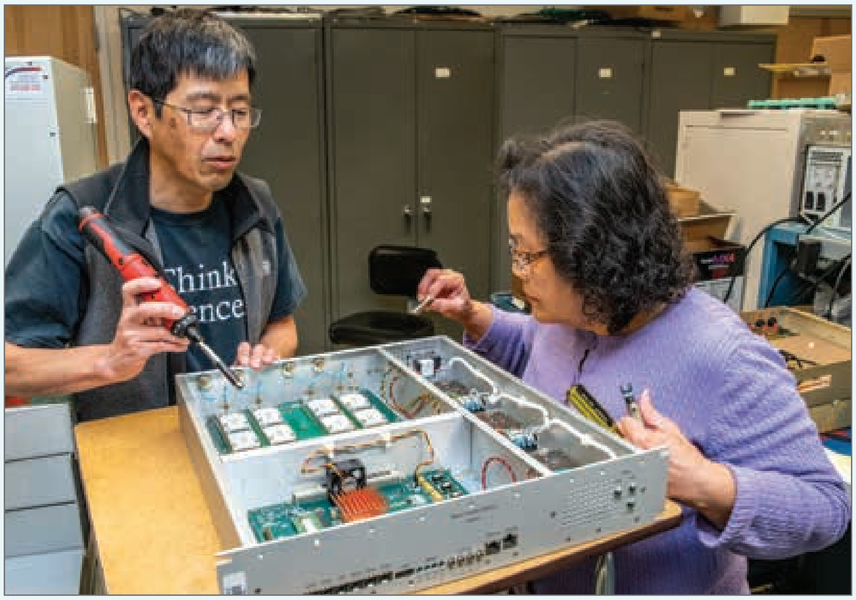
Dan Cheng (foreground) and Ahmet Pekedis fabricate and test a form for a prototype quadrupole magnet for the LHC in Berkeley Lab's superconducting magnet assembly facility.

LINAC COHERENT LIGHT SOURCE-II (LCLS-II)

LCLS-II, a free-electron laser facility being built at SLAC National Accelerator Laboratory by a multi-lab partnership, depends on several major contributions from Berkeley Lab. The Physical Sciences Area team includes mechanical, magnetics, and radio-frequency engineers, physicists, mechanical designers, fabrication shop personnel, and assembly technicians. Engineering-intensive LCLS-II contributions include the electron injector source, undulator modules, and the low-level radio-frequency (LLRF) control system.



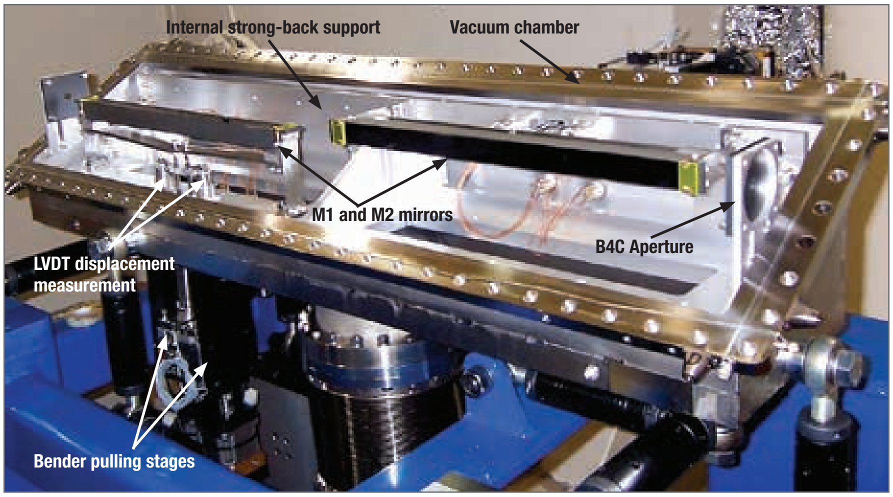
This 8-stage bipolar inductive voltage adder using power MOSFETs has been designed to drive fast stripline kicker magnets, which are required for on-axis swap-out injection for the ALS-U project. This prototype has been demonstrated with a kicker magnet in the ALS storage ring and further development activities are pursuing improved rise and fall times of its 5kV, 50ns pulses.



Mike Chin and Helen Chen test a beam position monitor (BPM) for the ALS. This beyond-state-of-the-art technology will enable both unprecedented control (position accuracy) and throughput (positions measured per second), resulting in unprecedented electron beam stability and correction capability.

ACCELERATOR ENGINEERING 5–10 YEAR GOALS

- Lead ALS Upgrade project engineering and related R&D efforts, culminating in a successful ALS-U start-up in the mid 2020s; key technologies include magnet, vacuum, RF, structures and vibration isolation, and opto-mechanical engineering.
- Design, develop, and fabricate high-field magnets for the HL-LHC AUP.
- In partnership with the U.S. Magnet Development Program, develop novel superconducting magnet designs, technologies, and materials that, if successful, could revolutionize HEP collider capabilities and enable compact medical accelerators and light source performance beyond the current state of the art.
- Support the expansion and development of the BELLA Center and its compact laser-plasma accelerators.

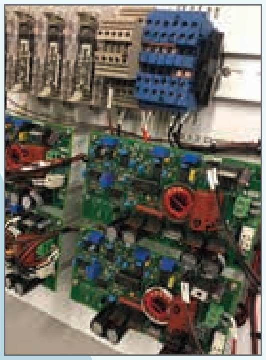


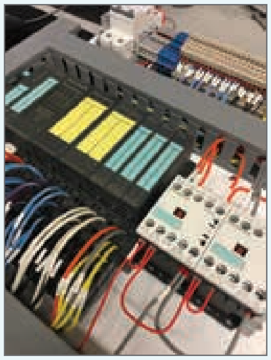
Berkeley Lab-developed deformable mirrors in Kirkpatrick-Baez geometry are used for an atomic, molecular, and optical (AMO) physics beamline at SLAC's Linac Coherent Light Source.

X-RAY OPTICS AND BEAMLINE DESIGN

X-rays from synchrotron or FEL light sources are delivered to experimental endstations. Berkeley Lab Engineering has developed specialized instrumentation, including bendable cooled and uncooled X-ray optics, monochromators, and endstations, and works with partners to produce complete turnkey solutions for this ultrahigh-vacuum environment.

Over the coming years, this expertise in opto-mechanical engineering will be vital to ALS-U as the team develops next-generation wavefront-preserving X-ray optics. Engineering also develops X-ray detector systems and other detectors for application in existing light sources, as detailed in a later section.





Throughout the Lab, the Engineering Division provides safety systems and interlock designs to protect personnel from hazards such as radiation, electrical energy, and laser light. The interlock system for the Berkeley Lab Laser Accelerator is an example of Engineering's safety-systems design. Interlocks are designed using technologies ranging from electromechanical relays and commercial off-the-shelf (COTS) components to custom designs based on Programmable Logic Controllers (PLCs), which allow for complex logic and self-checking. Engineering works with customers at all phases: from requirement and specification generation and management through system design, installation, and technical oversight.

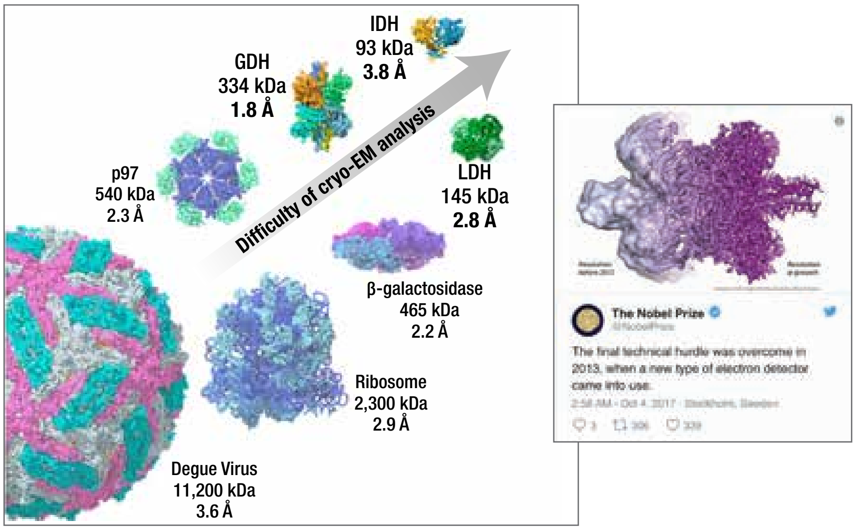
DETECTOR SYSTEMS

From house-sized detectors at high-energy-physics colliders to precision devices at light-source beamlines, from CERN to the ice of the South Pole, and in disciplines ranging from nuclear science to biology, detectors enable experiments to produce data. Integrating expertise in large-scale systems with several deep competencies in design of semiconductor detectors and integrated circuits, the Engineering Division serves Berkeley Lab and the nationwide and global scientific community by helping design and build state-of-the-art radiation detectors.

MULTICHANNEL SENSOR READOUT ELECTRONICS AND SOLID-STATE IMAGING SENSORS

Berkeley Lab has been developing advanced solid-state imaging detectors and systems for visible light, electron, and soft X-ray sources for over 20 years.

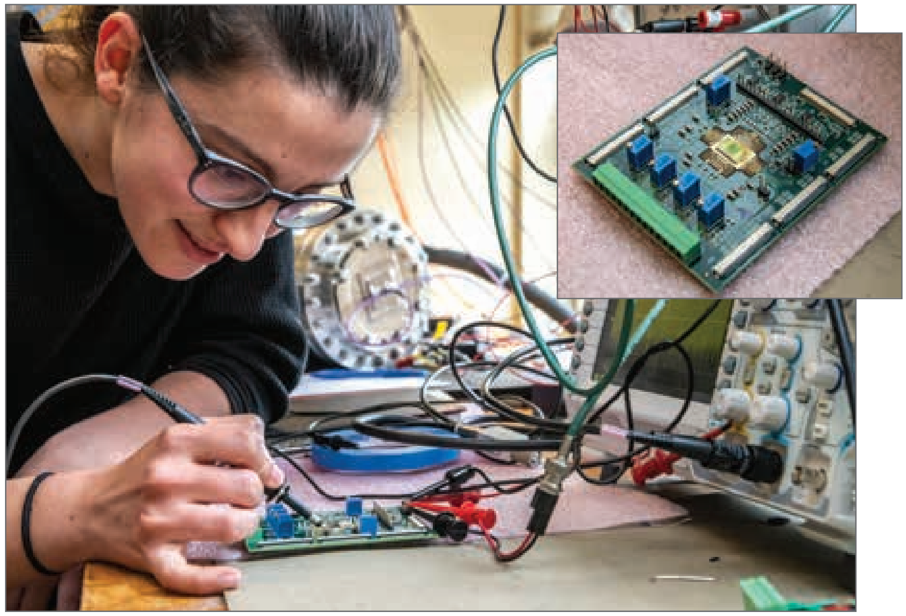
A particular success story comes from electron microscopy, which now uses direct electron imagers. Berkeley Lab's Engineering Division developed a complementary metal-oxide-semiconductor (CMOS) sensor dubbed "K2" and transferred the technology to Gatan Inc., which has commercialized a complete Transmission Electron Microscopy (TEM) imaging sensor system. The 2017 Nobel Prize in



K2 has brought improved resolution to cryo-electron microscopy, enabling imaging resolution at the single-atom level.

DETECTOR ENGINEERING 5–10 YEAR GOALS

- Develop and deliver state-of-the-art instrumentation, imaging, data acquisition and triggering systems for emerging detector systems worldwide supporting the high energy physics, nuclear science and photon science communities.
- Pioneer imaging technology instrumentation advances, including semiconductor sensors and direct detection of photons and electrons using silicon detectors for use in synchrotrons, FELs, and transmission electron microscopy facilities.
- Advance the state of the art in on-line digital processing, data streaming, and large-channel-count ASICs for, e.g., neural data acquisition and stimulation for neuroscience and brain research.
- Advance the state of the art in deeply cryogenic electronics and micropower autonomous sensor systems, and apply these advancements to research problems of scale in biology, energy, and earth sciences.



Katerina Papadopoulou performance tests the state-of-the-art 4D STEM chip, a CMOS active pixel sensor for high-speed electron microscopy to be installed at Berkeley Lab's National Center for Electron Microscopy.

Chemistry affirmed K2's role in the new field of cryo-electron microscopy with the statement that "The final technical hurdle in Cryo-EM was overcome in 2013, when a new type of electron detector came into use."

The development of improved CMOS sensors for electron microscopy continues. K3, a 24-megapixel sensor operating at 1,500 frames per second, has since been developed and commercialized.

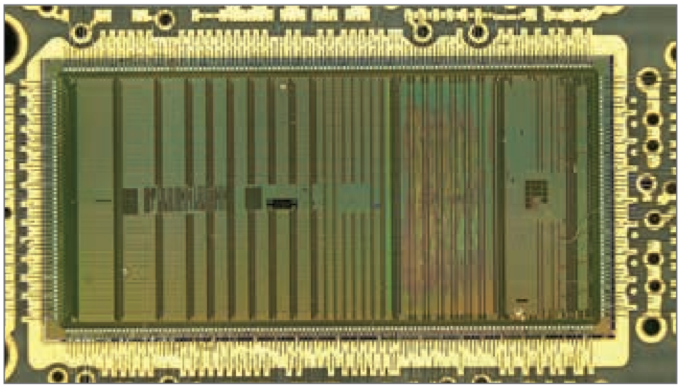
In addition to high-performance CMOS sensors, the Engineering Division also develops charge-coupled devices (CCDs) and associated readout algorithms and application-specific integrated circuits (ASICs) to provide cameras for very-high-speed imaging applications focused primarily on soft X-ray microscopy.

CUSTOM INTEGRATED CIRCUITS OPEN THE PATH TO HIGH-PERFORMANCE DETECTORS AND IMAGING DEVICES

The Engineering Division's IC group develops integrated circuits for a variety of applications, especially for particle detector and scientific imager readout. We focus on providing high-channel-count, mixed-signal chips for extreme environments (e.g., high-radiation, low-temperature, or in-vacuum operation) where suitable commercial parts do not exist.

The Division's core capabilities include ultra-low-noise analog front ends, high-performance data converters, CCD-imager clock drivers, and CMOS active-pixel sensors for scientific imaging. Design capabilities cover a wide range of IC technologies, including mixed-signal, silicon-on-insulator (SOI), and high-voltage CMOS, with delivery of ICs fabricated in CMOS process nodes from 3 microns down to 65 nanometers.

We also are working on electronics that operate at liquid helium temperature and below, opening a path to integrated instrumentation to enhance monitoring and safety for superconducting magnets. In addition, we are building upon recent efforts in neural recording and sensing to address challenges in bioelectrical interfaces, such as brain-machine interface applications. Finally, we are investigating the potential for custom programmable processors, based on the open-source RISC-V instruction set, to efficiently execute specific algorithms.



24-channel readout ASIC for electron microscopy with 4.5 Gb/s serial digital output — a large advance over previously available performance.

FUTURE DIRECTIONS FOR DETECTOR READOUT ELECTRONICS

Engineering's strategic vision is to use evolving technologies and new approaches to meet ever-more-difficult challenges. Future experimental apparatus with new requirements and higher data rates, often operating in harsher environments (e.g., amid higher radiation fields or at cryogenic temperatures), will need innovative technologies and designs. For example, future field-programmable gate arrays (FPGAs) and systems-in-a-package technology (SiP) will allow the configuration of full systems in a single component. Emerging design tools and methods promise increased productivity, allowing complex FPGA and ASIC and other complex circuits and systems. Meanwhile, capabilities of COTS modules are expanding while their costs go down. These trends will impact future development of scientific instrumentation.

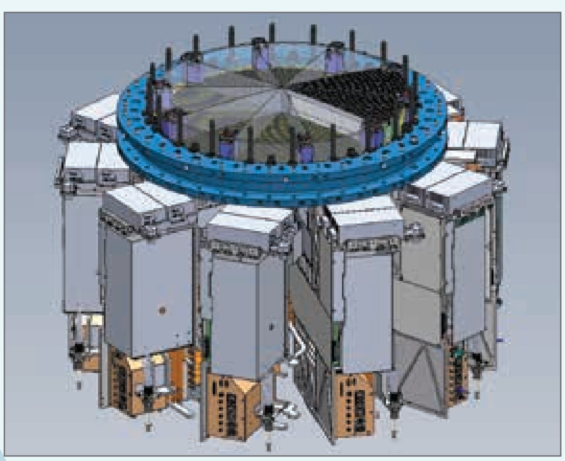
LARGE DETECTOR SYSTEMS

LUX-ZEPLIN (LZ)

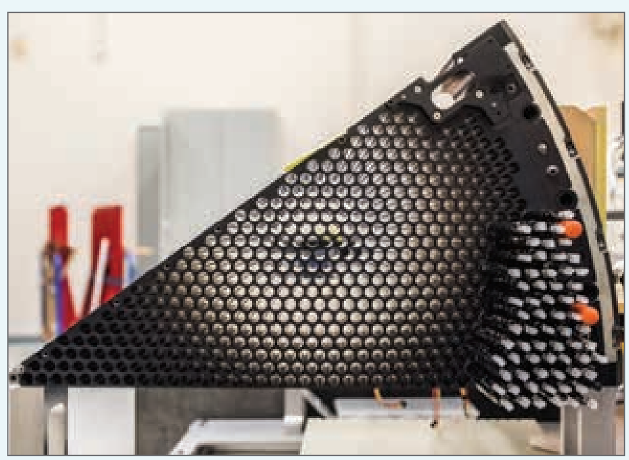
The visible universe is vast and complex, yet gravitational effects indicate that we are only seeing about 5 percent of it. Theorists have concluded that about one fifth of the mass of the universe must be "dark matter" of a yet-unknown nature. To study dark matter particles, the LZ experiment will utilize 7 metric tons of liquid xenon as an active detection medium to find them. LZ is being built by a multi-institutional collaboration. The Engineering Division's contributions include project management and controls, lead engineering, mechanical design of major systems, high-voltage expertise, and installation and facility integration support.

DARK ENERGY SURVEY INSTRUMENT (DESI)

The complement of dark matter in the mystery of the invisible universe is "dark energy," thought to make up about two-thirds of the mass of the cosmos. To detect it, Berkeley Lab's Physics Division, supported by Engineering, is leading a project called the Dark Energy Survey Instrument (DESI), a 5,000-fiber multi-object spectrograph with robotic fiber positioners, to measure the expansion history of the universe.



DESI's 5,000 robotic positioners are close-packed, with their tips placed on the aspheric focal plane. The focal plane system contains around 800,000 individual parts in a 2.3-cubic-meter volume.



Approximately 300 positioners are assembled in a DESI petal.

The objective of the instrument is to measure 35 million galaxies and quasars during a 5-year period of astronomical observations. To achieve this, Engineering has designed and built a focal plane with 5,000 individually controlled robots. These miniaturized robots reposition optical fibers to the desired location on the focal plane with a 5 μm accuracy.

Berkeley Lab is the lead laboratory for the project and is directly responsible for the focal plane design as well as construction, assembly, and installation at the Mayall Telescope in Arizona.

GAMMA-RAY ENERGY TRACKING ARRAY (GRETA)

The atomic nucleus holds vital information about the nature and origins of visible matter. At the Facility for Rare Isotope Beams (FRIB), a major accelerator-based nuclear-physics project being built at Michigan State University, the Berkeley Lab-designed GRETA will help unlock these secrets. Engineering is contributing to this Nuclear Science Division-led project through design and fabrication of electronics, mechanical, and computing systems, in addition to providing project management and controls.

CAD rendering of GRETA, which will support 30 detector modules, giving complete 4-pi coverage of the volume.

CROSS FUNCTIONAL SUPPORT 5–10 YEAR GOALS:

- Develop direct 3D modeling to fabrication capabilities.
- Integrate augmented reality into CAD design tools.
- Implement quality assurance workflow and requirements tracking in the Product Lifetime Management (PLM) system.

LARGE SCALE DETECTOR COMPOSITE STRUCTURES

At the leading edge of high-energy and nuclear physics, even structural supports demand high-technology components. Tracking detectors require support structures with low mass (to reduce Coulomb scattering of particle tracks), yet high strength; a detector assembly might take the form of a meters-long, fractional-millimeter-thick tube with a precision of tens of microns, supporting detectors that have 10 times the mass of the structure. From its beginnings with the ATLAS Pixel System for the LHC, the Engineering Division's composites capability has become a key resource for demanding projects such as upgrades at the Relativistic Heavy Ion Collider and continuing R&D for the HL-LHC. The next generation of colliders will require even larger detectors with greater requirements for stability (to enable more precise measurements), and with higher radiation tolerance, pushing the limits of the systems.

SHOPS, LABORATORIES, AND SUPPORTING FACILITIES AND SERVICES

The manufacturing and fabrication facility focuses on providing a broad range of technically advanced manufacturing resources to the scientific divisions and user facilities of the Laboratory at a level and convenience of service not available from commercial vendors. The focus is development of internal capabilities that

Advanced machine shop capability has always been and will remain key to building unique scientific instruments for the Lab. Continued modernization of machine tools and skills enables these capabilities. This panoramic view of machinists and equipment in the Engineering Division's Building 77 shop shows a set of tools available at the Lab.

are challenging to find in industry, and in forging extensive collaborations with industry. Specialized assembly facilities and personnel, including cleanroom capabilities, are available to support projects of all scales.

COMPOSITE LABORATORY AND ENGINEERING CAPABILITIES

The Composite Laboratory specializes in design and fabrication of high-performance carbon-fiber structures and precision-bonded assemblies (incorporating both metallic and composite components) for silicon tracking detectors and other specialized applications.

PRECISION METROLOGY, SURVEY & ALIGNMENT

The precision measurement facility serves an essential function in the quality assurance and alignment of the unique instruments and assemblies produced by the Engineering Division.

Precision survey and alignment is vital to the performance and sustainability of particle accelerators and other scientific facilities. The Survey & Alignment Group collaborates with projects. Engineering continually pushes state-of-the-art measurement technologies and methods to enable future accelerators and instrumentation.

PROJECT PLANNING AND CONTROLS

The Project Planning and Controls Department provides projects with expertise in planning and control, and implements an Earned Value Management System (EVMS) based on the ANSI/EIA-748 guidelines for complex projects across the Laboratory.

CROSS-FUNCTIONAL SUPPORT

The Engineering Division's Cross-Functional Support group provides a technical framework for how all division engineering and project tasks are implemented. This includes systems engineering, requirements management, configuration management, and applicable safety-basis documentation.

MANUFACTURING, MACHINING, AND MATERIALS 5–10 YEAR GOALS:

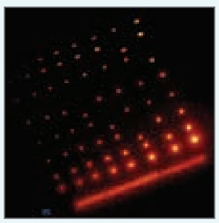
- Upgrade large-scale machining capability beyond what is available in industry.
- Push the envelope of precision manufacturing and measurement capabilities.
- Enhance additive manufacturing capabilities, including 3D metal printing.
- Develop composites, resins, and epoxies for harsh environments.

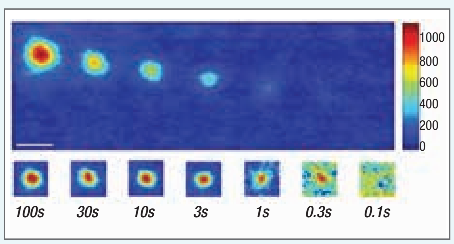
PROJECT PLANNING AND CONTROLS 5–10 YEAR GOALS:

- Develop project management and project planning methods that optimize the delivery of project scope, cost, and schedule.
- Develop integrated project management tools that enable forecasting studies during all phases of a project lifetime.

EMERGING CAPABILITIES

Quantum Information Science (QIS), which includes new methods for computing, communication and metrology that employ quantum mechanical phenomena, is of great current interest. The DOE Office of Science has launched a cross-cutting QIS initiative, in which Physical Sciences can play important roles in collaboration with University of California, Berkeley (UC-Berkeley); ATAP and Engineering are developing technologies to advance QIS in areas including quantum simulations with increasing numbers of superconducting qubits and quantum communication and sensing with novel color center qubits; Physics Division is working on ways of using quantum algorithms for data analysis and simulation, along with development of new, very sensitive detectors for dark matter searches; and the Nuclear Science Division is applying its expertise in cryogenic and complex detector instrumentation, as well as ion source development, to pursue enabling technologies for QIS.





Photoluminescence image of nitrogen-vacancy color centers formed by local exposure of a diamond sample to low energy electrons with increasing fluence. Color centers are promising for quantum computing, secure quantum communication and for quantum sensing. Scientists in ATAP are developing methods to improve the properties of color centers for applications in QIS.

Machine learning is another broad area of interest for the Office of Science with many applications for the Physical Sciences Area. Machine learning methods use statistical techniques to identify models of large data sets, which can then be used for prediction and inference.

These methods are increasingly important in science, and are being applied to data from telescopes, light sources, and simulations. But the uses in scientific fields also place new demands on these methods. For many problems, they need to extract features from data with a low signal-to-noise ratio and deliver results that are reproducible, interpretable to scientists, consistent with known physical laws, and have quantifiable uncertainties. At the same time, DOE has an opportunity to leverage its leadership in experimental science, simulation, and High Performance Computing (HPC) to apply machine learning to scientific data at unprecedented scale and complexity.

Physical Sciences Area researchers are participating in several projects as part of a Laboratory-wide initiative in Machine Learning for Science. Topics being studied include the derivation of cosmology parameters from astronomical data sets, and classification of jets and other phenomena from collider experiments, as well as studies of the underlying assumptions and applicability of the method.

As experimental data sets become steadily larger and more complex, our Area will have many opportunities to leverage these emerging capabilities.

SCIENCE IN SOCIETY

Physical Sciences Area R&D has wide-ranging direct benefits to society. Our powerful particle beams help test commercial satellites' electronics to simulate conditions in Earth's orbit and ensure our communications networks can endure the rigors of space. Detectors born of the quest to understand subatomic particles help protect against smuggling of weapons materials and have analyzed the consequences of the Fukushima accident (page 32). Particle accelerators are even used to treat cancer – and a new generation of ultracompact accelerators could make treatments easier, better, and more affordable. Here are just a few examples of practical benefits from our basic research.

The examples below are some of the efforts in Science for Society that offer important technical advances benefiting humankind well into the future.

ACCELERATING FIELDS RANGING FROM CANCER THERAPY TO NUCLEAR SECURITY

New modalities for acceleration, beam transport, and detectors are being explored with colleagues from UC San Francisco; UC Davis; and Berkeley Lab's Biosciences Area. We are also improving proton and heavy-ion therapy by developing smaller and lighter beam-delivery "gantries" based on innovative superconducting magnets (page 39). Left: Workshop on an advanced particle-therapy research facility, held at UCSF in 2018.

Another of the many LPA applications involves a compact, near-monoenergetic source of MeV photons. The long-term goal is a safe, quick way to detect nuclear material hidden and shielded within large objects, such as shipping containers.

AUDIO PRESERVATION – BENEFITS THROUGHOUT RECORDED HISTORY

Physical Sciences researchers developed a no-touch way to scan, analyze, and recover sound from priceless and fragile early recordings. Their approach combines two techniques developed for high energy physics — data analysis that finds particle tracks amid background "noise," and precision metrology for detector-chip inspection. The Smithsonian Institution is among the users of the technique, digitizing historic recordings, and one of the inventors, Carl Haber, was honored with a MacArthur Foundation "genius" grant. Right: Carl Haber (holding record) and Vitaly Fadeyev use their sound restoration device.

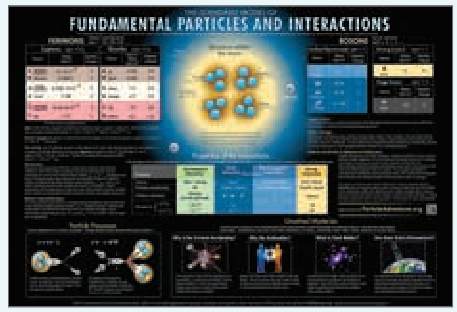
USING APPLIED SCIENCE TO COPE WITH A DEADLY LEGACY OF WAR

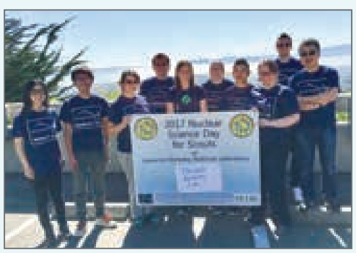
Unexploded ordnance (UXO) is a distributed humanitarian catastrophe that can lurk for many decades after the end of a war. The Berkeley UXO Discriminator is a multisensor electromagnetic system that brings unprecedented speed and accuracy to the task of differentiating buried UXO from harmless metal, as well as determining the location, size, and shape of potential explosives. Berkeley Lab's Earth Sciences Division partnered with the Engineering Division on the UXO system.

COMMUNITY OUTREACH AND EDUCATION

The Physical Sciences Area has a broad commitment to communicating what we have learned, what we hope to explore in the future, and how physics research satisfies the fundamental human desire to understand the universe – with many practical benefits along the way. Here are just some of the higher-profile examples.

Physical Sciences staff have been active participants in the creation of the iconic Contemporary Physics Education project wallcharts that synopsize the Standard Model of Fundamental Particles and Interactions, Nuclear Science, and the History and Fate of the Universe. Favorites at high schools, universities, and laboratories around the world, the charts have been translated into several languages.





Since 2011, the annual Nuclear Science Day for Scouts has been attracting 150–180 young people for a fun and educational day – and a chance to earn a merit badge. This annual event, spearheaded by Alan Poon, is organized and made possible by volunteers from Physical Sciences in collaboration with Berkeley Lab's Advanced Light Source (ALS) Division and Workforce Development and Education Office (WD&EO). *Top photo credit: Erika Suzuki, NSD. Bottom photo credit: Peter DaSilva.*

Physical Sciences outreach and education efforts are coordinated with Labwide WD&EO programs. Staff members lead hands-on activities during onsite sessions, visit local schools with K-8 science kits, and lend their expertise to the Oakland Unified School District Science Fair; here Cameron Geddes and Ina Reichel show students how spectrographic gratings reveal what is occurring inside various kinds of light bulbs. Daughters and Sons to Work Day is another traditional favorite. *Photo credit: Caleb Cheung, Oakland Unified School District.*

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