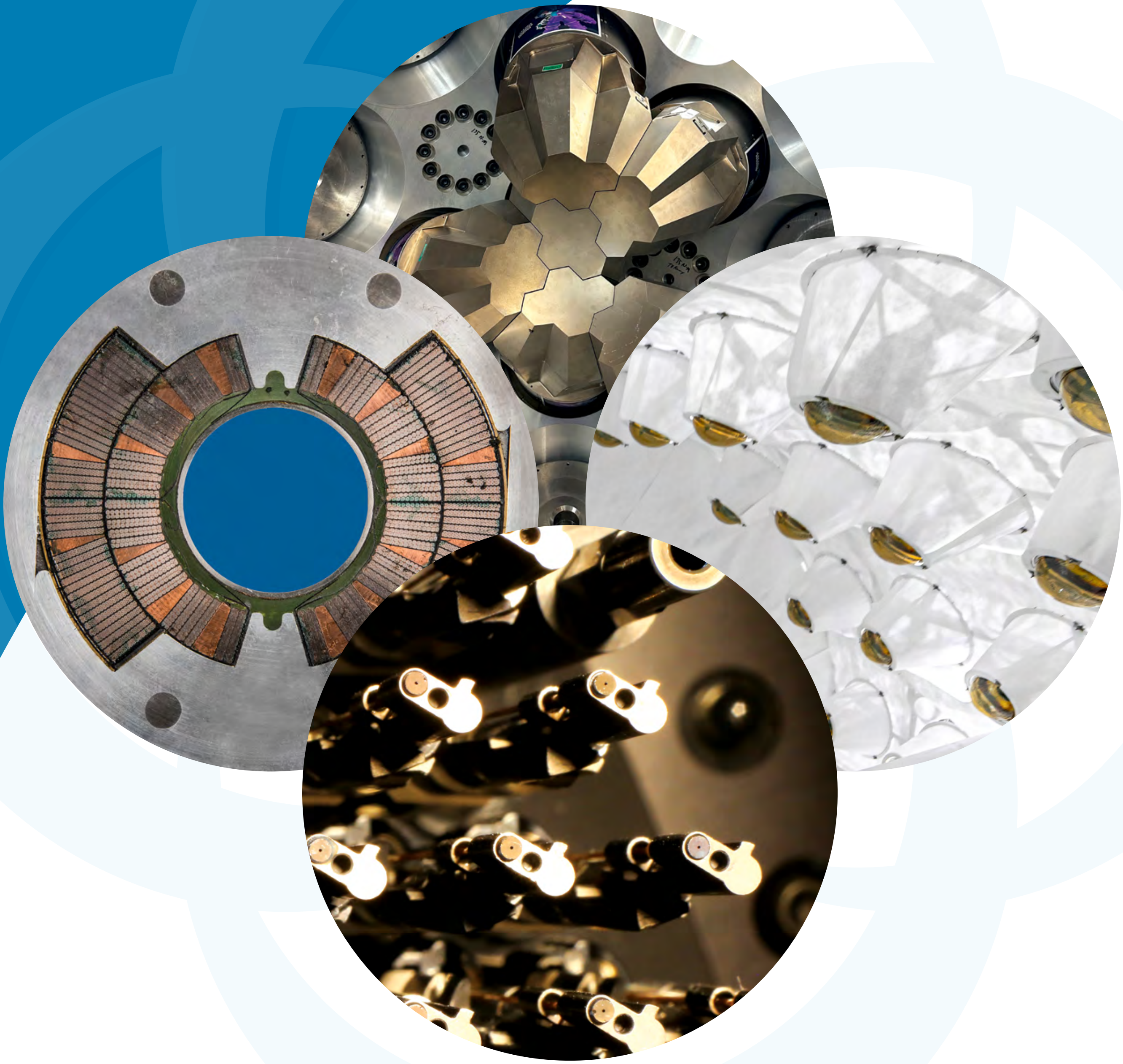
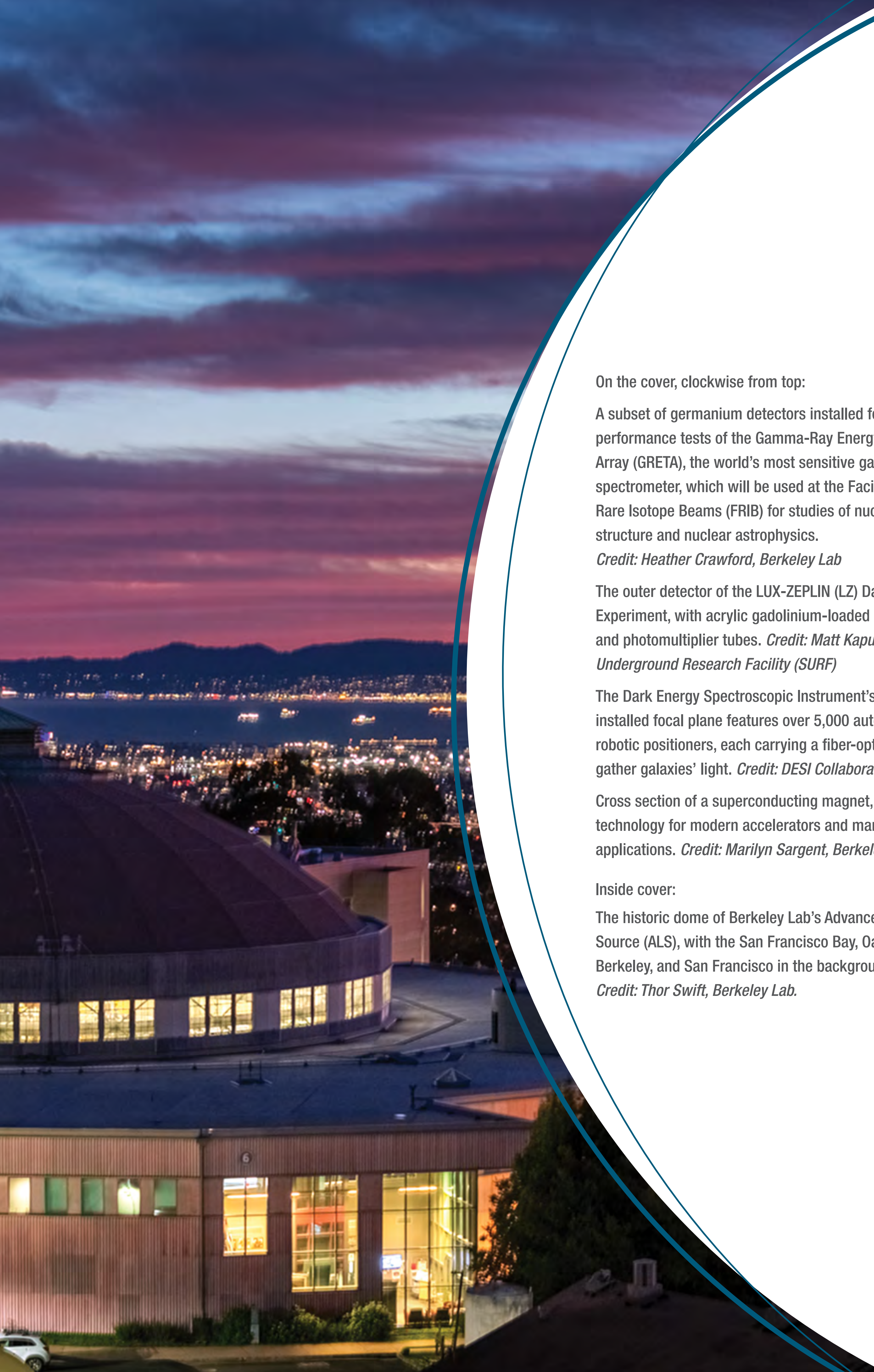
2025
PHYSICAL SCIENCES 10–YEAR STRATEGIC PLAN



BERKELEY LAB

PHYSICAL SCIENCES



On the cover, clockwise from top:

A subset of germanium detectors installed for performance tests of the Gamma-Ray Energy Tracking Array (GRETA), the world's most sensitive gamma-ray spectrometer, which will be used at the Facility for Rare Isotope Beams (FRIB) for studies of nuclear structure and nuclear astrophysics.
Credit: Heather Crawford, Berkeley Lab

The outer detector of the LUX-ZEPLIN (LZ) Dark Matter Experiment, with acrylic gadolinium-loaded scintillator and photomultiplier tubes. *Credit: Matt Kapust, Sanford Underground Research Facility (SURF)*

The Dark Energy Spectroscopic Instrument's (DESI) fully installed focal plane features over 5,000 automated robotic positioners, each carrying a fiber-optic cable to gather galaxies' light. *Credit: DESI Collaboration*

Cross section of a superconducting magnet, a vital technology for modern accelerators and many other applications. *Credit: Marilyn Sargent, Berkeley Lab*

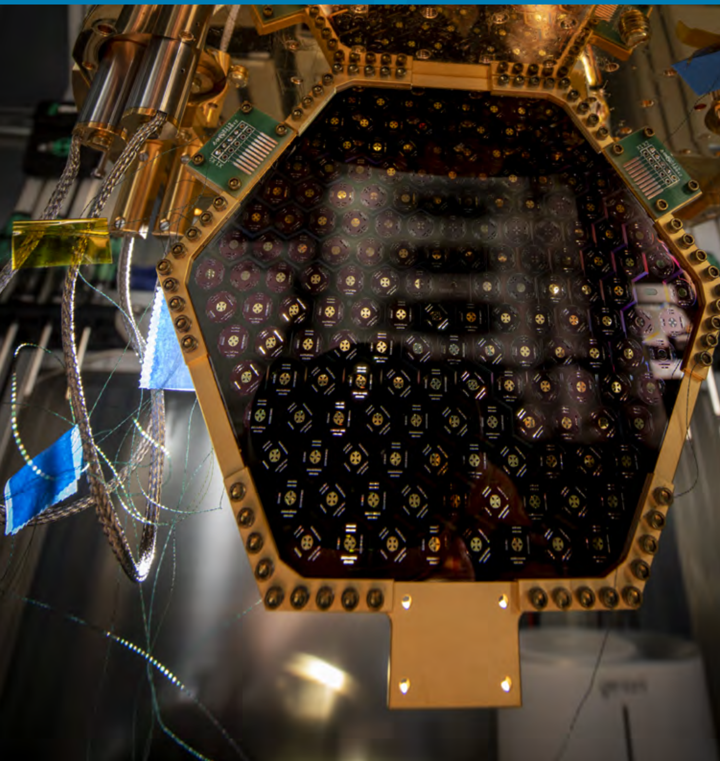
Inside cover:

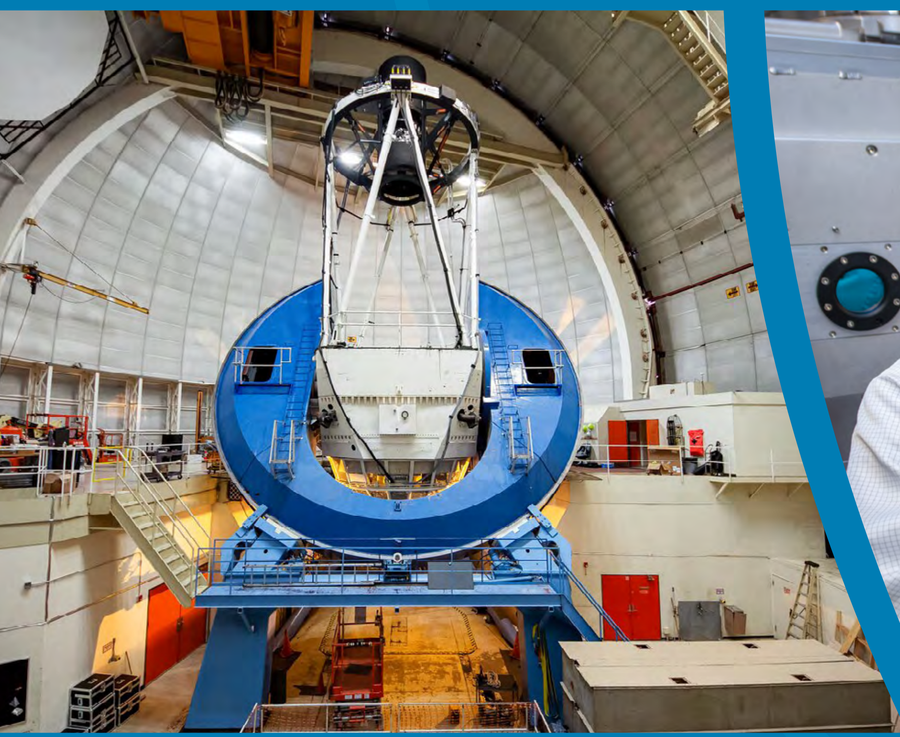
The historic dome of Berkeley Lab's Advanced Light Source (ALS), with the San Francisco Bay, Oakland, Berkeley, and San Francisco in the background.
Credit: Thor Swift, Berkeley Lab.

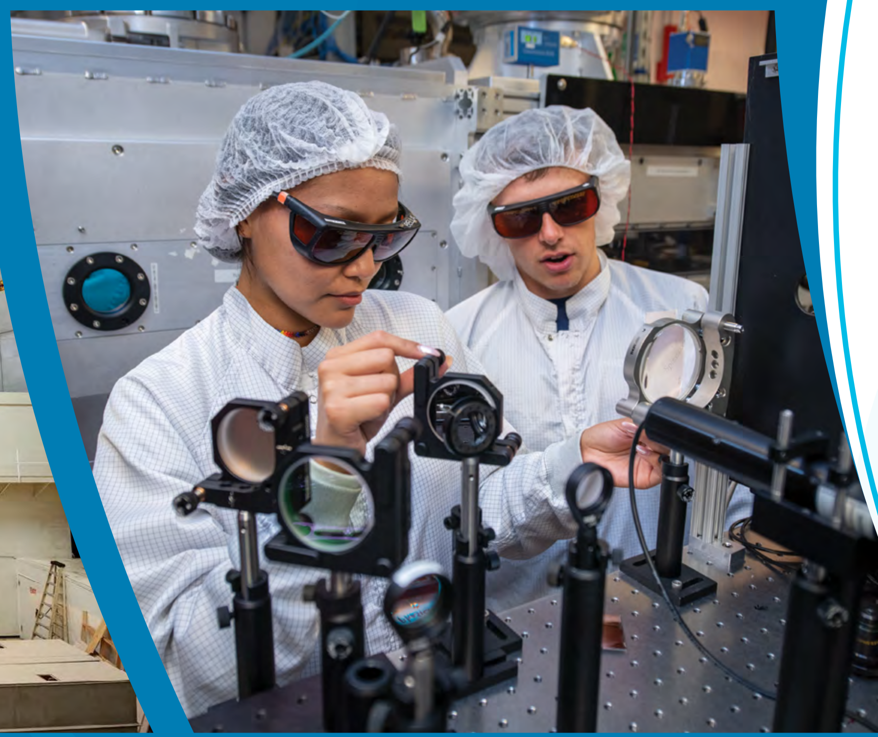
PHYSICAL SCIENCES

10-Year Strategic Plan

2025







The Cosmic Microwave Background Stage 4 (CMB-S4) Prototype Detector Array installed in the dilution refrigerator for cryogenic temperature characterization. *Credit: Thor Swift, Berkeley Lab*

Bottom left: The Dark Energy Spectroscopic Instrument (DESI) is installed on the Nicholas U. Mayall 4-meter Telescope at Kitt Peak National Observatory near Tucson, Arizona. *Credit: Marilyn Sargent, Berkeley Lab*

Top right: Members of the Cryogenic Underground Observatory for Rare Events (CUORE) Collaboration working on the CUORE cryostat. *Credit: Courtesy of CUORE Collaboration*

Bottom right: Research scientist Alex Picksley (right) and Hannah Nockideneh, a student intern from Arizona State University, finalize the alignment of the wavefront sensing diagnostic used to characterize plasma densities of the Berkeley Lab Laser Accelerator (BELLA) Center's novel gas targets. *Credit: Thor Swift, Berkeley Lab*

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1. INTRODUCTION

Welcome to the Berkeley Lab Physical Sciences Area 2025 Strategic Plan. This milestone publication presents an overview of the Physical Sciences Area, its role within the Berkeley Lab community, and our aspirations for the next decade. We have accomplished most of the five-year goals described in the 2018 Physical Sciences Area Strategic Plan, despite some unanticipated challenges. During the COVID pandemic from 2020 to 2022, we had limited physical access to Berkeley Lab facilities, and this period brought about profound changes in the way we work and interact. Throughout these challenging times, the area's dynamic and innovative research environment has continued to thrive, thanks to the combined efforts of our exceptional staff and strong support from the Department of Energy's (DOE) Office of Science, National Nuclear Security Administration, and other federal agencies.

The 2018 Physical Sciences Strategic Plan provided an excellent blueprint for the new Physical Sciences Area management team. Led by Associate Laboratory Director Natalie Roe, who succeeded James Symons in 2020, the Physical Sciences Area comprises four divisions: Accelerator Technology & Applied Physics (ATAP), led by Cameron Geddes since 2021; Physics, led by Nathalie Palanque-Delabrouille since 2021; Nuclear Science, led by Reiner Kruecken since 2022; and Engineering, led by Daniela Leitner since 2024. The area has also assembled a strong new supporting team consisting of an Area Deputy, a Senior Administrator, and an Area Communications Lead.

The refreshed Physical Sciences Area management team has brought new approaches and perspectives while remaining true to the core scientific mission: advancing the frontiers of discovery in nuclear science, particle physics, and cosmology, and developing new particle accelerators and detector instrumentation, theoretical frameworks, and high-performance computing (HPC). We continue to advance applied technologies that address societal needs in health, security, and energy. Additionally, we continue our commitment to the Lab's stewardship values in order to attract, develop and retain talented, dedicated professionals, as we build a more welcoming and supportive environment for our people.

Ernest O. Lawrence talking to workers near construction site of 184-inch cyclotron.

Highlights since 2018 in the Physics Division's programs in particle physics and cosmology include the completion of two major high-energy physics experiments—the Dark Energy Spectroscopic Instrument (DESI) and the LUX-ZEPLIN (LZ) Dark Matter Experiment—to tackle the grand challenges of dark energy and dark matter, respectively. Both projects were completed on schedule and within budget, and are currently in the operations phase producing world-leading results. We have also pioneered a new pixel detector based on a custom application-specific integrated circuit (ASIC) that can function in the cryogenic environment of a liquid argon time projection chamber, and we are leading the technical scope for the Near Detector based on this technology for the Deep Underground Neutrino Experiment (DUNE), a megaproject led by Fermi National Accelerator Laboratory (Fermilab). We are applying our long-standing expertise in vertex detectors to support the upgrade of the inner tracking systems of the A Toroidal LHC Apparatus (ATLAS) detector for the high-luminosity upgrade of the Large Hadron Collider (LHC) at CERN (the European Organization for Nuclear Research).

In the Nuclear Science Division, we have made important contributions to the upgrades of vertex detectors of the A Large Hadron Collider Experiment (ALICE) heavy-ion experiment at the LHC and the sPHENIX experiment at Brookhaven National Laboratory (BNL). We are using these detectors to study the properties of the quark-gluon plasma. We also plan on making major contributions to the vertex detector for the Electron-Ion Collider (EIC), also at BNL. We are leading the Gamma-Ray Energy Tracking Array (GRETA) Project, fabricating a unique gamma-ray spectrometer that will be installed at the Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) and will be essential for the study of unstable nuclei. We have published world-leading results on neutrinoless double beta decay with the Cryogenic Underground Laboratory for Rare Events (CUORE) and CUPID-Mo (CUORE Upgrade with Particle Identification in Molybdenum) experiments, and we are leading the next-generation successor project, CUORE Upgrade with Particle IDentification (CUPID).

In the ATAP Division, we are developing new compact laser-plasma accelerators (LPAs) that could transform accelerator-based science of all types as dramatically as Ernest O. 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 treatments to homeland security. We are developing new types of superconducting high-field magnets to enable future colliders to reach even higher energies, and applying our expertise toward the fabrication of magnets for the High-Luminosity Large Hadron Collider (HL-LHC) upgrade at CERN and toward future fusion systems. We also lead exascale computing simulations and feedback controls essential for developing the next generation of accelerators as well as the science of light source and fusion systems.

The Engineering Division is the home of our advanced engineering and unique technical capabilities, together with strong project management capabilities. These strengths support the experimental efforts within the Physical Sciences Area and more broadly across Berkeley Lab, ensuring that we contribute effectively to the national program as we design, build, and operate new facilities and experiments, working collaboratively with our many partners in the US and abroad.

We invite you to peruse this publication to learn more about the Physical Sciences Area's research, projects, capabilities, and the groundbreaking scientific discoveries we hope to achieve.

Natalie Roe

ASSOCIATE LABORATORY DIRECTOR FOR PHYSICAL SCIENCES

Cameron Geddes

DIRECTOR, ACCELERATOR TECHNOLOGY & APPLIED PHYSICS (ATAP) DIVISION

Daniela Leitner

DIRECTOR, ENGINEERING DIVISION

Reiner Kruecken

DIRECTOR, NUCLEAR SCIENCE DIVISION

Nathalie Palanque-Delabrouille

DIRECTOR, PHYSICS DIVISION

VISION

Our vision is to understand the fundamental physics of the universe at scales ranging from the infinitely small, inside the world of subatomic particles and nuclei, to the infinitely large, in the structure and evolution of the cosmos. We develop cutting-edge tools and technologies, coupled with creative scientific insights, that advance scientific knowledge and benefit society.

MISSION

Our mission is to carry out research on the fundamental nature of matter through programs in cosmology, particle physics, nuclear science, and accelerator science in support of the DOE Office of Science mission. We develop, deploy, and operate experiments at a wide range of facilities around the world located deep underground, on mountaintop observatories, and at accelerator laboratories. We design and build new particle accelerators and detectors pushing the boundaries of technology, with broad applications in science, medicine, energy, and security. Our staff are world experts in the design, engineering, and execution of major scientific projects. We analyze massive data sets and carry out simulations on the most advanced supercomputers, and develop new theoretical models that describe natural phenomena in the language of mathematics.

2. FIVE- AND TEN-YEAR HORIZONS

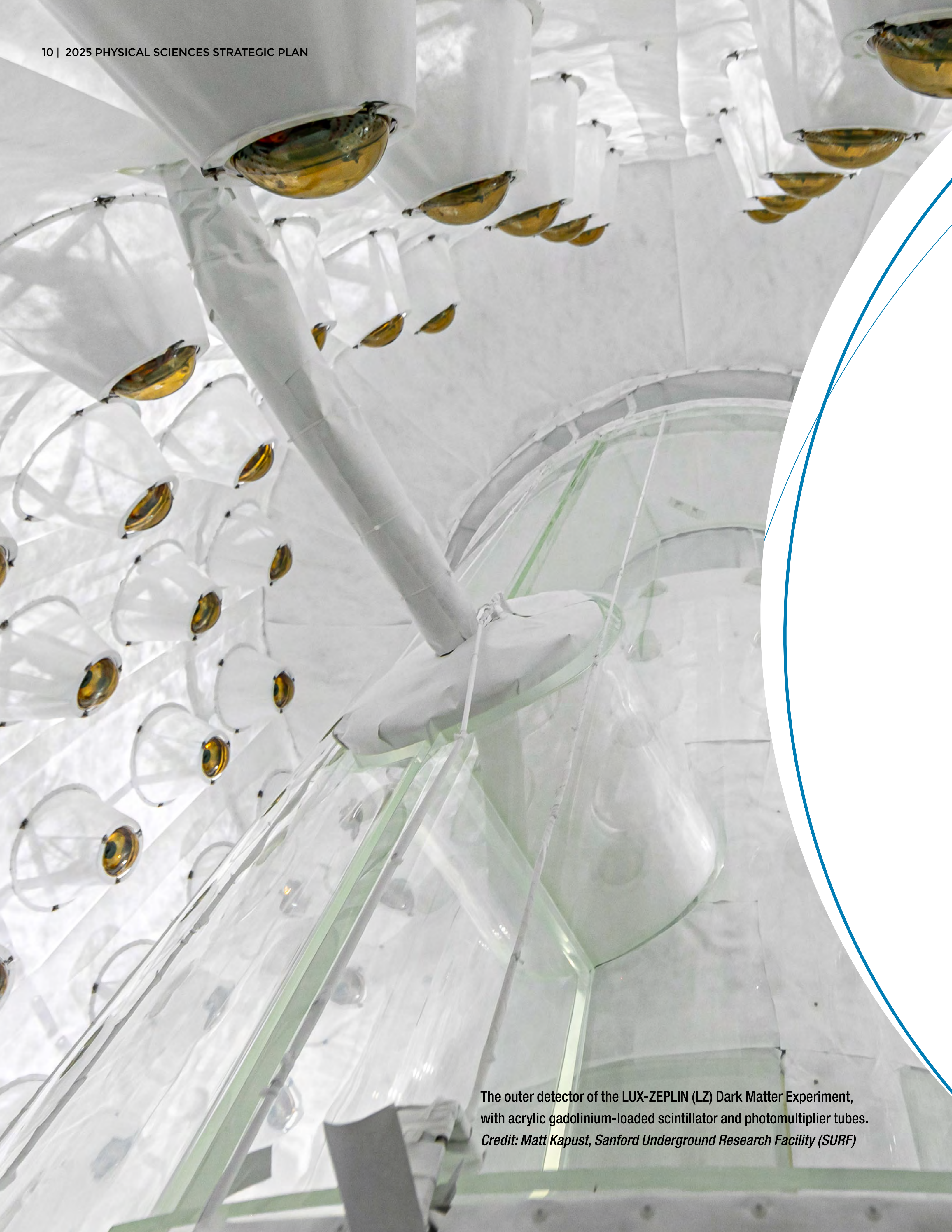
The Physical Sciences Area is deeply rooted in the history and traditions of Berkeley Lab, which was founded in 1931 by Ernest Lawrence. His invention of the cyclotron, together with the team science approach he pioneered, enabled the rapid progression from small hand-size accelerators to larger and larger machines, in the pursuit of cutting-edge discoveries in nuclear and particle physics. This team approach to science continues today, enabling us to design and build experiments to tackle seemingly intractable problems and address fundamental questions about the nature of our universe.

Today in the Physical Sciences Area, we have a well-balanced program ranging from research and development of new technologies, to project design and execution of major new facilities, to advancing new methods in theory, computation, and data analysis. Strategic planning is done within the divisions, beginning with a grassroots approach to encourage staff to develop new concepts and explore new ideas. The Laboratory Directed Research and Development (LDRD) program is an important source of funding for these explorations. At the next level of planning, key decisions are made at division retreats and in discussions with group leaders about which opportunities to pursue, considering alignment with the DOE mission as well as our ability to make appropriate, national lab–scale contributions. We are active participants and leaders in the community planning processes that set the important strategic directions for our scientific disciplines, and our programs are well aligned with the recommendations of the 2023 Particle Physics Project Prioritization Panel (P5) Report, *Exploring the Quantum Universe: Pathways to Innovation and Discovery in Particle Physics*, the 2023 US Nuclear Science Long Range Plan, *A New Era of Discovery*, and the plans of other offices we work with. These documents lay out 10-year plans for the particle physics and nuclear science communities, respectively, working within budgetary scenarios provided by the DOE funding agencies and incorporating community input to determine which experiments should be supported.

On the five-year horizon, the Physical Science Area has a broad and exciting scientific program of experiments already in progress that are searching for dark matter, making precise measurements of dark energy, studying the Higgs boson and the quark-gluon plasma, measuring neutrino properties, and searching for new heavy elements, to name just a few research topics. In accelerator science, we are making great strides in laser-plasma acceleration, superconducting magnet technologies, heavy-ion injectors, beam measurement and control instrumentation, and simulation. New research areas in quantum science and machine learning have matured into a significant part of our portfolio. The Engineering Division plays a key role in our major projects, in addition to major roles in the upgrade of the Advanced Light Source.

On the 10-year horizon, we are developing several new projects that build on our expertise, including the next generation of accelerators, and new experiments in nuclear physics, particle physics, and cosmology. Because these tend to be large, expensive projects that can take many years to design, construct, and operate, we take a long-range view, even beyond 10 years, and make investments in technologies and research and development (R&D) to develop our long-term scientific vision. While this strategic plan has a 10-year horizon, it looks well beyond that, towards future opportunities that will benefit from investment in new technologies today.

The view from Lawrence Berkeley National Laboratory (Berkeley Lab) looking towards Oakland and the San Francisco Bay. *Credit: Thor Swift, Berkeley Lab*



The outer detector of the LUX-ZEPLIN (LZ) Dark Matter Experiment, with acrylic gadolinium-loaded scintillator and photomultiplier tubes.
Credit: Matt Kapust, Sanford Underground Research Facility (SURF)

3. PARTICLE PHYSICS AND COSMOLOGY

3.1 EXECUTIVE SUMMARY AND STRATEGIC PILLARS

3.1.1 MISSION

The Physics Division's mission is to explore the nature of the universe from its largest to its smallest scales, and to understand its fundamental constituents, history, and evolution. To achieve this mission, we lead our physics program from start to finish, with the division playing key roles at all stages: from the conception of projects to their design, construction, commissioning, operations, and data analysis. Building on the interpretation of the results, we then initiate the conception of a new generation of projects.

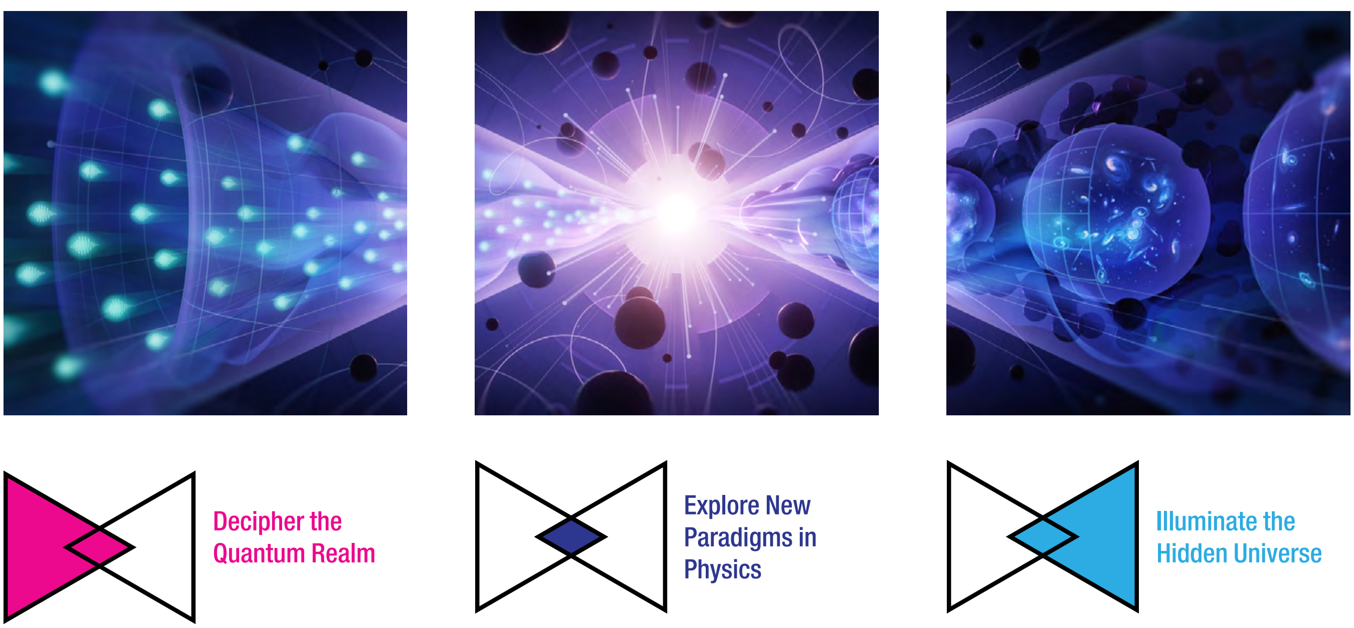


Illustration from the 2023 Particle Physics Project Prioritization Panel (P5) Report, *Exploring the Quantum Universe: Pathways to Innovation and Discovery in Particle Physics*, which shows the three overarching science themes that were identified as the most promising avenues of investigation for the next 10 to 20 years.

3.1.2 OVERVIEW OF PARTICLE PHYSICS AND COSMOLOGY P5 SCIENCE DRIVERS

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. Berkeley Lab's particle physics and cosmology research and capabilities, along with its accelerator work, are poised to address the recommendations from the 2023 P5 Report, which include support for several current large-scale efforts as well as for research and development (R&D) for future projects.

The essential components of the Berkeley Lab physics program of discovery for the coming decade (and of its accelerator program as described in Section 5) ideally align with the P5 science drivers:

- **Elucidate the mysteries of neutrinos.** Berkeley Lab has a key role in designing and prototyping the Near Detector for the Deep Underground Neutrino Experiment (DUNE), building on a long and successful history in neutrino physics with the KamLAND and Daya Bay experiments. The Dark Energy Spectroscopic Instrument (DESI) galaxy redshift survey will also shed light on neutrino masses through their impact on structure formation in the universe.
- **Reveal the secrets of the Higgs boson and search for direct evidence of new particles.** Berkeley Lab has a large group using the A Toroidal LHC Apparatus (ATLAS) detector experiment at CERN (the European Organization for Nuclear Research) to study the nature of the Higgs boson and search for new physics produced in high-energy collisions at the Large Hadron Collider (LHC). Several group members also play leading roles in the ATLAS detector upgrades for the High-Luminosity Large Hadron Collider (HL-LHC) project. Together with colleagues in the Accelerator Technology & Applied Physics (ATAP) Division, the ATLAS group is working to design and develop detectors and accelerators for future colliders, including a Higgs factory and a collider at the 10 TeV per parton scale.
- **Pursue quantum imprints of new phenomena.** Berkeley Lab has a key role in the Muon-to-Electron Conversion Experiment (Mu2e) at Fermi National Accelerator Laboratory (Fermilab), which will be sensitive to new physics at much higher mass scales than the LHC.
- **Determine the nature of dark matter.** Berkeley Lab leads the LUX-ZEPLIN (LZ) Dark Matter Experiment. LZ is installed at the Sanford Underground Research Facility (SURF) and is currently the most sensitive search for weakly interacting massive particles (WIMPs), dark matter particles with masses in the range 10–1000 GeV. Berkeley Lab is also engaged in R&D toward upgrades for LZ, and is leading the development

of novel technology for low-mass dark matter searches with transition-edge sensors (TESs): the Transition-Edge Sensors with Sub-eV Resolution And Cryogenic Targets (TESSERACT) experiments.

- **Understand what drives cosmic evolution.** Berkeley Lab leads the DESI experiment, which is mapping the expansion history of the universe with exquisite precision to study dark energy and test general relativity. Berkeley Lab is also the lead lab for the CMB-Stage 4 (CMB-S4), the next-generation cosmic microwave background (CMB) experiment to detect the signal from primordial inflation. Berkeley Lab is preparing for the DESI-2 survey and conducting R&D for a future Stage 5 spectroscopic survey.

PHYSICS RESEARCH

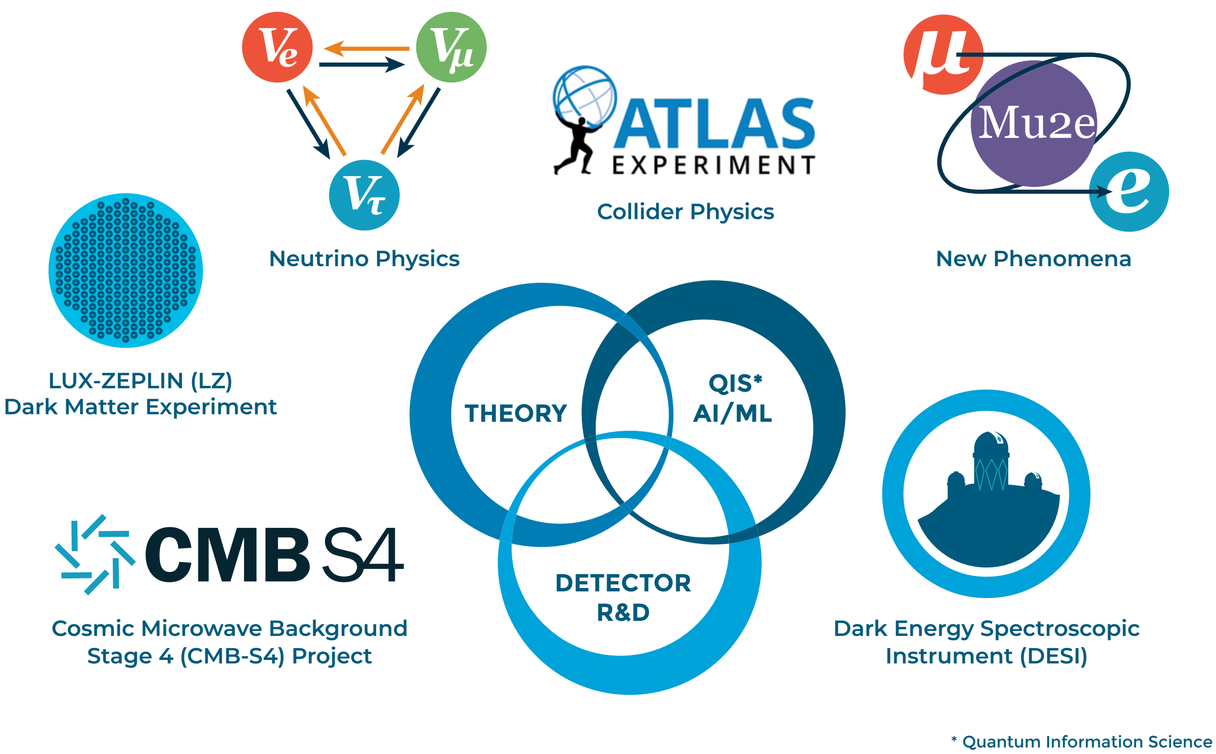
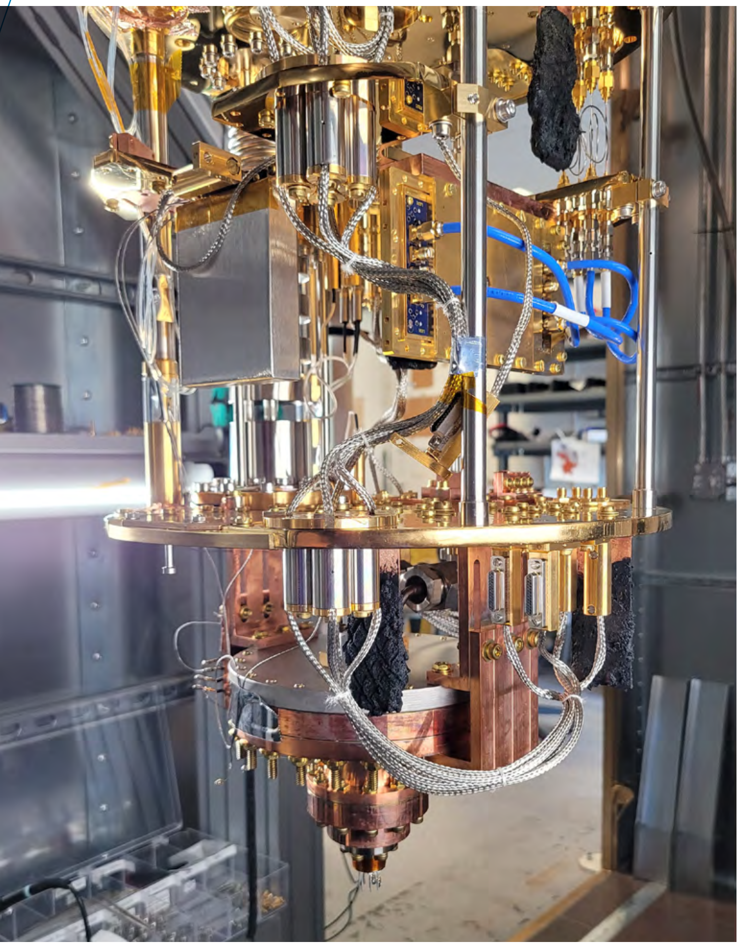


Illustration showing the Berkeley Lab Physics Division's engagement in a broad and ambitious experimental program covering energy, intensity, and cosmic frontiers of particle physics with strong interconnections.



Cold stage of a dilution refrigerator, to be operated at mK temperatures, a prototype for the TESSERACT experiment's dark matter search. *Credit: Peter Sorensen, Berkeley Lab*

3.1.3 WIDE-RANGING CAPABILITIES

Berkeley Lab brings unique strengths and capabilities to these physics programs, including the following:

- **Detector innovation** is a traditional Berkeley Lab strength that opens new avenues for experimental investigations. Our expertise in instrumentation contributes to innovations in microelectronics. Experimental techniques developed in high-energy physics are used to advance quantum information science, which in turn contributes to novel developments for dark matter research.
- **Advanced computing, artificial intelligence (AI), and machine learning (ML)** are increasingly important and enabling components of all DOE Office of High Energy Physics (HEP) research, both within and across programs. We leverage expertise at Berkeley Lab's National Energy Research Supercomputing Center (NERSC) and Energy Sciences Network (ESnet) to benefit HEP projects, and we collaborate extensively with data scientists in the Computing Sciences Area and at the University of California, Berkeley (UC Berkeley).
- **Theoretical studies** directly benefit current experimental efforts at Berkeley Lab and across the broader US program, informing current and proposing future research directions.
- **The Particle Data Group** (PDG) is led by Berkeley Lab. The PDG produces a comprehensive and authoritative annual compilation of world averages and underlying results, together with expert reviews covering all fields of particle physics and related cosmological measurements.
- **A strong partnership with UC Berkeley** brings faculty and students to Berkeley 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.

3.2 SCIENCE AND DISCOVERY

3.2.1 REVEAL THE SECRETS OF THE HIGGS BOSON AND SEARCH FOR DIRECT EVIDENCE OF NEW PARTICLES: ATLAS AND FUTURE COLLIDERS

The CERN LHC collides protons at the highest energy of any facility. Since 1993, the Berkeley Lab group has contributed to one of its two multipurpose experiments, ATLAS. Since then, the group has produced world-class measurements and held major coordination roles in the ATLAS Collaboration. A major upgrade of the ATLAS detector is essential for continued operations in the HL-LHC era, making it possible to investigate rare phenomena predicted by the Standard Model of particle physics and explore new physics. The HL-LHC is scheduled to begin operation in 2030.

A key element of the physics program is to study properties of the Higgs boson, including characterizing its couplings with third-generation fermions and establishing evidence for its yet unseen coupling to second-generation fermions. The Berkeley Lab ATLAS group is producing new world-best measurements with the data collected so far. It played a leading role in recent first observations of rare processes, including four top-quark production and photon-induced production of a pair of W bosons. It will continue to pave the way in experimentally establishing rare unobserved phenomena that can test our current theories and open a window on how to further develop them. Interactions between Berkeley Lab's ATLAS Group and Theory Group, through monthly joint seminars, are an essential component in generating new ideas and designing strategies to search for new particles or fundamental interactions in the LHC data.

Together with colleagues in the Applied Mathematics and Computational Research Division (AMCRD), Berkeley Lab's ATLAS Group has designed and maintained algorithms, software infrastructure, and simulation of the detector, all of which play a vital part in data analysis. By leveraging major contributions in developing multi-threaded software and new charged-particle reconstruction algorithms, which are vital to analyze the huge datasets within the computing budget available, the group is preparing the experiment for the HL-LHC era. Data volumes will increase by almost a factor of 10, and heterogeneous computing resources will be essential to analyze data and produce adequate simulations. Developing fast simulations, including using AI/ML techniques and hardware accelerators as graphics processing units (GPUs), and heavily relying on central processing unit (CPU) multithreaded applications, is an active area of research and synergy with the AMCRD.

The upgraded ATLAS detector will have increased capabilities, enabling more precise measurements despite the higher collision rates. Berkeley Lab is the only US lab with simultaneous responsibilities on ATLAS strips, pixels, and mechanics

FIVE-YEAR GOALS

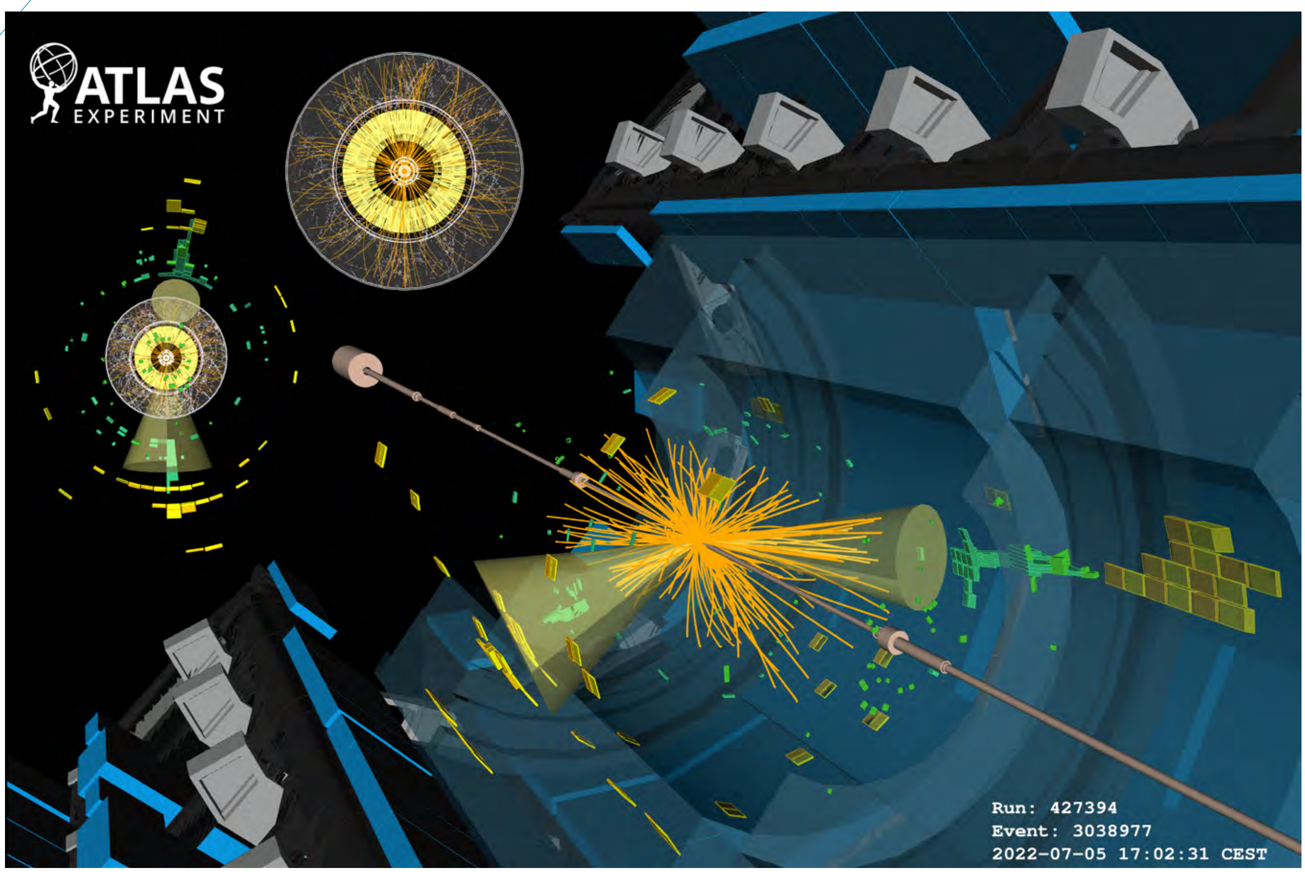
- Conduct precision Higgs and electroweak measurements and searches for new physics with ATLAS Run 3 data.
- Complete construction and testing of silicon pixel and strip modules; participate in installation and commissioning of the ATLAS ITk (Inner Tracker) upgrades for the High-Luminosity Large Hadron Collider (HL-LHC), at CERN.

TEN-YEAR GOALS

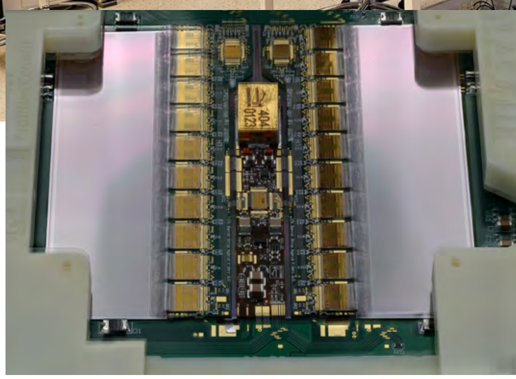
- Produce first physics results using the HL-LHC.
- Engage in planning and pursuing R&D toward an offshore Higgs factory and a 10 TeV pCM (parton center-of-momentum, or parton center-of-mass) collider.

for this upgrade. These efforts include scientific staff as well as technical and engineering personnel, including extensive carbon-fiber expertise and application-specific integrated circuit (ASIC) design expertise from the Engineering Division. The group plans to continue its involvement past the construction phase and into the commissioning and installation of the detector at CERN.

While exploiting the large HL-LHC dataset to its fullest potential, the group is also engaging in planning the next-generation collider. Active R&D into front-end ASIC based on 28nm technology for pixel detectors is a key element in our quest to enable fast timing and more on-chip processing capabilities in addition to exquisite spatial resolution. The group is investing in developing fast readout technology based on optical transmission in very high-radiation environments



Event display (graphical representation) of a candidate four top-quark event from data collected in 2016. The event contains seven jets, which are complex clusters of particles created via interactions mediated by the strong force. Three of the top quarks produce leptons in their decay, and the fourth top quark decays to jets. The two x-y projections are those viewed from either end of the detector. *Credit: ATLAS Collaboration/CERN*



Berkeley Lab cleanroom where the ATLAS ITk Silicon Strips modules are assembled. *Credit: Alessandra Ciocio, Berkeley Lab*

Inset: ITk strip detector module prototype built at Berkeley Lab. *Credit: Timon Heim, Berkeley Lab*

and innovative materials for the sensing elements in such detectors, to play a leading role in delivering these technologies. Detectors in proposed future colliders will have very high demands in these areas and will not be possible without such technologies.

Fundamental physics at the energy frontier requires large collaborative projects. The Berkeley Lab group is positioning itself to continue its key role in enabling these projects through a unique and wide mix of cutting-edge technologies, innovative computing developments, and world-best physics results.

Anne Fortman, a Berkeley Lab postdoctoral fellow, explains the ATLAS silicon detector readout electronics to visiting high school students. *Credit: Laura Guthrie, Acalanes High School*

FIVE-YEAR GOALS

- Complete prototyping and start construction of the DUNE Near Detector.

TEN-YEAR GOALS

- Commission and begin data taking with DUNE Phase I; publish initial oscillation measurements.

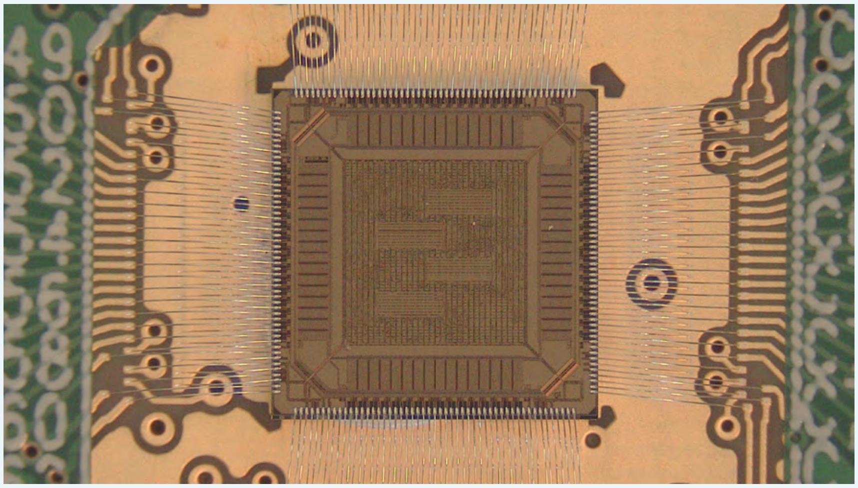
3.2.2 ELUCIDATE THE MYSTERIES OF NEUTRINOS: DEEP UNDERGROUND NEUTRINO EXPERIMENT (DUNE)

Through experiments at reactors and accelerators, and cosmological observations, Berkeley Lab researchers are developing new methods to tackle key open questions in neutrino physics: Is charge parity (CP) symmetry violated in neutrino oscillations? What is the correct mass hierarchy? What is the sum of neutrino masses? Does a light-sterile neutrino exist? Researchers in the Physics Division aim to answer these questions, while scientists in the Nuclear Science Division lead experiments to elucidate other properties of neutrinos, such as whether they are their own antiparticle.

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 have provided US leadership for both the KamLAND and Daya Bay experiments, which have provided the most definitive evidence of neutrino flavor oscillation. Through precise measurement of antineutrinos emitted by nuclear reactors, these two experiments have measured four of the six parameters defining the three-flavor model of neutrino oscillations.

The DUNE experiment, which will direct an intense neutrino beam from Fermilab to a very large liquid argon time projection chamber detector located underground in South Dakota, will be the flagship experiment for the US neutrino program for the next 10 to 20 years. A critical component of this experiment is the Near Detector at Fermilab to characterize the neutrino beam and carry out a broad program of neutrino interaction studies. Berkeley Lab provides US leadership to develop DUNE's Liquid Argon Near Detector (ND-LAr), as well as engineering management for the entire Near Detector complex. Berkeley Lab also contributes expertise for designing the cold electronics inside the cryogenic detector for the Near Detector and Far Detector, and has developed a novel 3D pixelated readout system to cope with the large number of simultaneous events in the Near Detector. Berkeley Lab leads the 2x2 Demonstrator effort, an ND-LAr prototype including more than 300,000 pixels that will be used to characterize neutrino-argon interactions in the energy regime for DUNE. The software for DUNE requires sophisticated algorithms and a powerful computing infrastructure. Berkeley Lab physicists, together with computer scientists from the AMCRD and NERSC, are leading the software and computing development for the DUNE Near Detector.

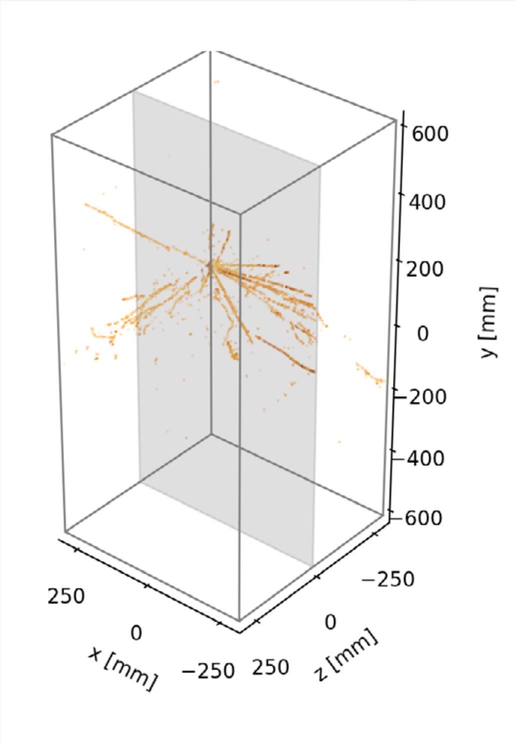
Finally, the DESI experiment will provide entirely complementary constraints on the sum of the neutrino masses from a detailed map of cosmic structure. Learn more about DESI in Section 3.2.5.



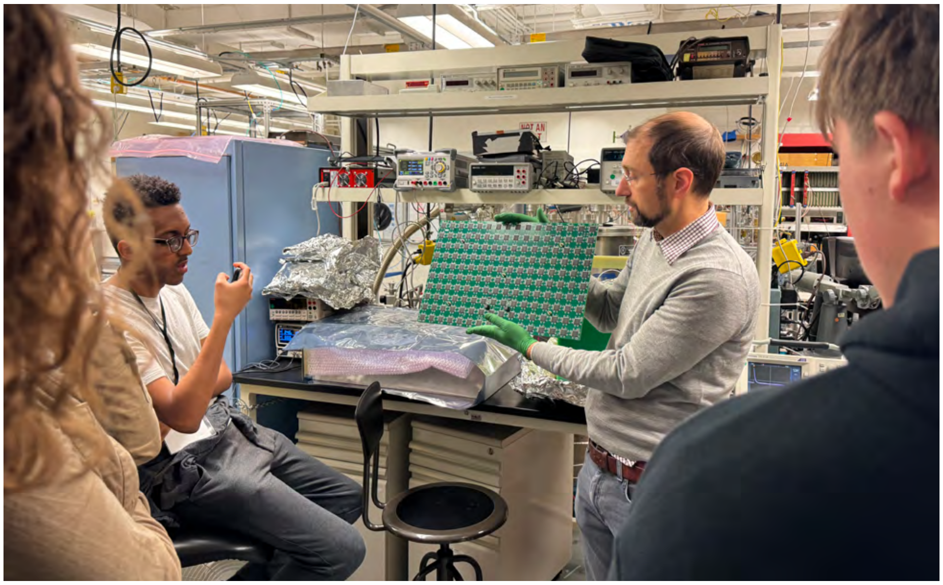
Magnified image of the LArPix-v2b ASIC die. *Credit: Phathakone Sanethavong, Berkeley Lab*

DUNE'S LArPix ASIC

Berkeley Lab physicists and engineers conceived, developed, and built a prototype 3D pixelated detection system for DUNE. The LArPix (Liquid Argon Pixel) system is an ASIC that implemented cryo-stable transistor behavior to use an incredibly power-efficient amplifier to minimize heat while preserving performance. The new electronics use less than 100 microwatts per channel, roughly 1,000 times less power than typical detector electronics. Learn more about the Physical Science Area's efforts for DUNE in Section 6.3.2.1.



3D display of a cosmic ray interaction imaged in the prototype pixelated LArTPC. *Credit: Dan Dwyer*



Dan Dwyer, head of Berkeley Lab's Neutrino Physics Group, explains LArPix tile to visiting prospective graduate students. *Credit: Anthony Spadafora, Berkeley Lab*

FIVE-YEAR GOALS

- Commission Mu2e tracker. Play a leading role in analysis of first data, with a target sensitivity of 1e-15. Begin R&D on detectors for next-generation muon charged lepton flavor violation (CLFV) experiments.

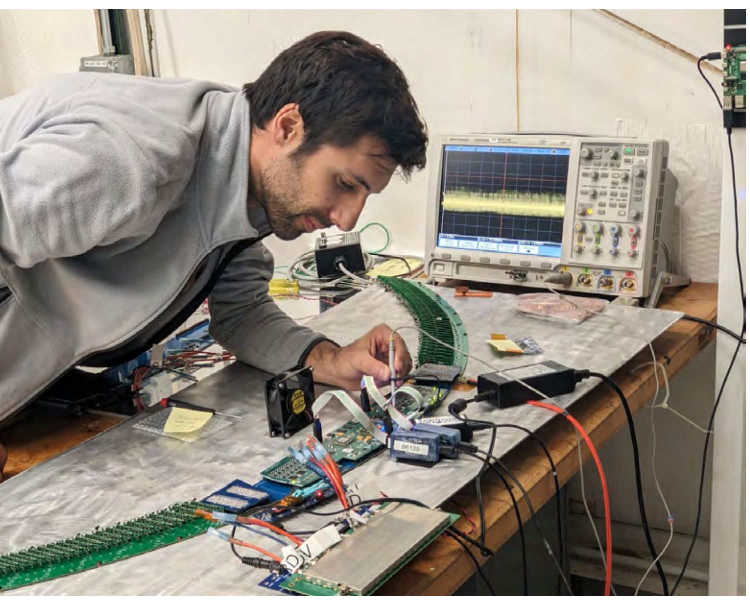
TEN-YEAR GOALS

- Complete the full Mu2e beam run and analysis, with a target sensitivity to CLFV of 1e-17. Prototype next-generation muon CLFV detectors and electronics.

3.2.3 PURSUE QUANTUM IMPRINTS OF NEW PHENOMENA: MUON-TO-ELECTRON CONVERSION EXPERIMENT (Mu2e)

One possible signature for new physics is the observation of charged lepton flavor violation (CLFV): for example, a muon changing to an electron. Neutrino oscillations provide evidence of lepton flavor violation. But charged lepton flavor transitions without neutrino emission have never been observed, though they are predicted by most beyond the Standard Model (BSM) theories. The Mu2e experiment, under construction at Fermilab, will search for muon conversion into an electron in the field of a nucleus, a promising channel for CLFV detection. Given the prodigious rate of muon production possible at the Fermilab muon campus, coupled with a novel experimental design that greatly reduces fake conversion signals from "background" particles, Mu2e will reach unprecedented sensitivity.

Berkeley Lab has been a member institution of Mu2e for 14 years and has made major contributions to the design and construction of the tracker, electronics, triggering, firmware, and software. The group is active in developing the tracker firmware and data acquisition system, and the track reconstruction, calibration, and simulation algorithms. It holds management positions in the overall experiment, in the general software organization, and in the calibration and alignment of the detector.



Richie Bonventre, a staff scientist in the Mu2e Group and the PDG, tests the firmware design for the Mu2e tracker electronics.
Credit: Dave Brown, Berkeley Lab

The Berkeley Lab group will help install and commission the tracker detector and participate in the first search for CLFV at Mu2e. The first run of data is expected to be sensitive to a muon-to-electron conversion rate of 10^{-15}, three orders of magnitude better than current limits. With its second run, Mu2e will reach another order of magnitude in sensitivity. If a signal is observed, we will test different target materials to discriminate between models of new physics. In addition, the Berkeley Lab group will begin the design and construction of the next-generation muon CLFV experiment.

We will also begin R&D efforts toward a Mu2e upgrade (Mu2e-II) and a future muon program at Fermilab. Mu2e-II will require detectors able to handle higher rates and radiation doses, while also achieving better resolution. We will explore new modular physical designs, modular electronics based on radiation-hard custom ASICs, and ML algorithms based on field-programmable gate arrays (FPGAs) for faster readout and triggering.

3.2.4 DETERMINE THE NATURE OF DARK MATTER

Astrophysical observations stretching back at least 80 years, including recent studies of the behavior of stars and galaxies, CMB measurements, and gravitational lensing data, have clearly established that about only 15% of the gravitationally interacting matter in the universe is normal baryonic matter. The remaining 85% is dark matter, which is invisible to observations across the optical spectrum, and is detected primarily by its gravitational effects.

Extensive studies suggest that dark matter must be some exotic form of matter. WIMPs have long been a favored candidate. Recent years have seen an increased theoretical interest in light dark matter models such as asymmetric dark matter, supersymmetric hidden sector dark matter, strongly interacting massive particles, and elastic decoupling relic dark matter. 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 SURF in Lead, South Dakota.

Berkeley Lab leads the LZ experiment, installed at SURF's 4,850-foot level nearly a mile underground. LZ is a strong international collaboration, with more than 250 scientists and engineers, and is one of the two major Generation 2 dark matter experiments in the US. The first engineering run of LZ, in 2023, led to world-leading sensitivity in the search for WIMPs with masses in the 10–1,000 GeV range. The LZ experiment is presently in a several-year-long operation period, extending the experiment's sensitivity to unprecedented levels and looking forward to finding the first evidence for particle dark matter.

Regardless of whether LZ observes suggestive events for dark matter scattering, the field is already considering the best experiment to pursue next. The XLZD Dark Matter Detection Consortium — an international consortium of researchers from LZ, the XENON Dark Matter Project, and the DARkmatter WImpsearch with liquid xenoN (DARWIN) Project—is interested in building a new, 10-times-larger detector, which would ultimately be limited in sensitivity only by the irreducible flux of astrophysical neutrinos. Berkeley Lab is pursuing R&D toward the realization of such an instrument, while also considering the possibility that the LZ infrastructure could pursue new scientific goals if upgraded.

Berkeley Lab is exploring two primary paths for an LZ upgrade:

- CrystaLiZe: crystallizing the liquid xenon can reduce beta-decay backgrounds from radon by a factor of 500 or more. This would leave astrophysical neutrinos as the dominant background.
- HydroX: doping helium or hydrogen into the liquid xenon would provide optimal kinematic matching to dark matter particles with masses in the 1–10 GeV range.

FIVE-YEAR GOALS

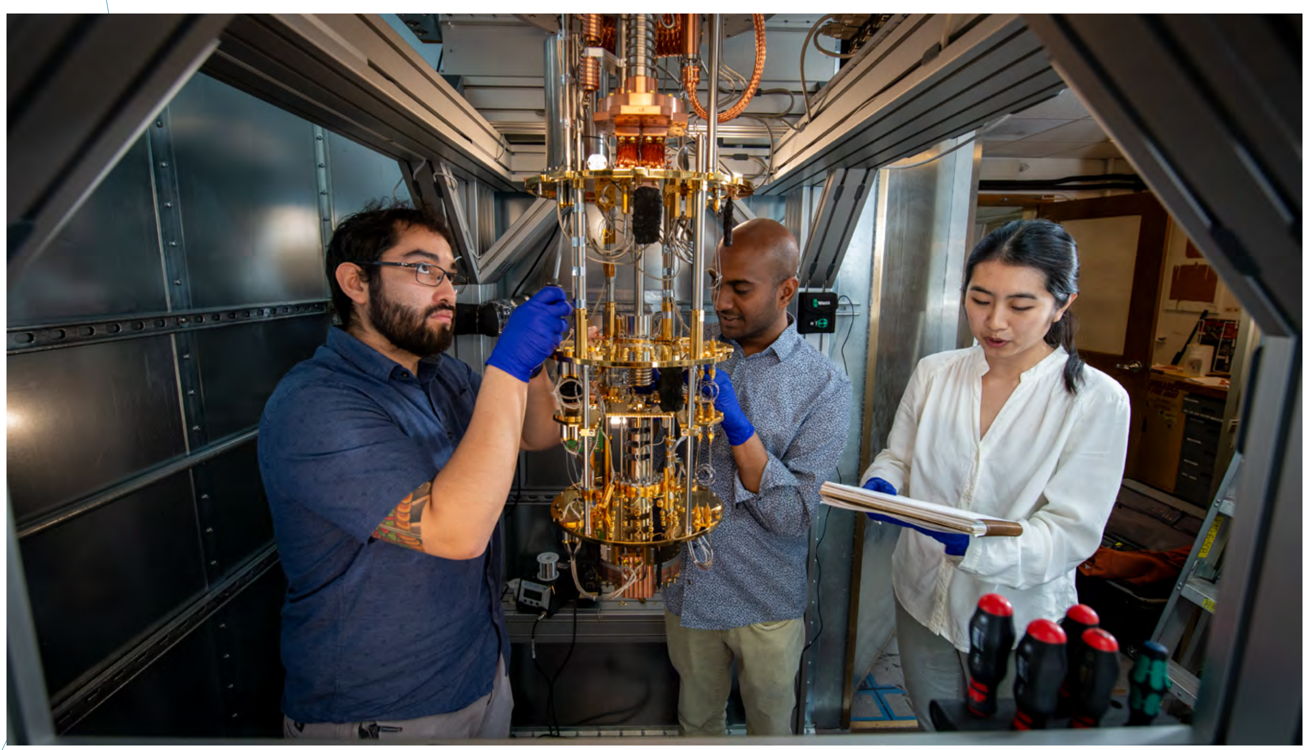
- Complete LZ runs to obtain design sensitivity to WIMP dark matter.
- Pursue R&D for upgrades of LZ to extend sensitivity to low-mass dark matter.
- Construct the TESSERACT dark matter detectors; commission and begin operations.

TEN-YEAR GOALS

- Pursue R&D enabling an LZ upgrade for improved light-mass dark matter sensitivity.
- Broaden the search for dark matter beyond LZ through upgrades and/or targeted low-mass dark matter searches.
- Publish world-leading results from the first set of TESSERACT detectors.

Dark matter may have mass below 1 GeV. To address this hypothesis, Berkeley Lab is leading the development of new detectors in the TESSERACT project, which is part of the Dark Matter New Initiative portfolio. TESSERACT is a collaboration to deliver the shielding, cryogenics, calibration tools, detectors, and project management necessary to achieve the collaboration's scientific goal of leading the sub-GeV dark matter search over the next decade.

For TESSERACT, Berkeley Lab is developing superfluid helium, gallium arsenide, and sapphire targets with a common TES readout. These detectors will be sensitive to a wide range of dark matter particle masses, and to dark matter that interacts preferentially with nuclei, electrons, or a crystal lattice. In addition, the TESSERACT technologies can discriminate between dark matter interactions and those arising from radioactive and instrumental backgrounds. We plan to deploy and operate two set ups within the next five years, to allow for the operation of all three technologies and some underground optimization of the detectors in one cryostat while performing dark matter searches simultaneously in the second cryostat. Achieving this goal would immediately lead to exploring uncharted parameter space.



Chamberlain Postdoctoral Fellows Michael Williams and Vetri Velan, and UC Berkeley Graduate Student Yue Wang, install sensors and superconducting readout equipment in the dilution fridge for the TESSERACT Experiment. *Credit: Thor Swift, Berkeley Lab*

3.2.5 UNDERSTAND WHAT DRIVES COSMIC EVOLUTION: LARGE-SCALE STRUCTURE OF THE UNIVERSE

The experimental cosmology program at Berkeley Lab, in partnership with the UC Berkeley cosmology group, forms a leading center for cosmological studies in the world, focused on the following:

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

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 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, Rubin Observatory (from the ground) and Roman Observatory (from space) will identify orders of magnitude more supernovae to be subsequently observed with other telescopes for spectroscopic typing and redshifts. A method developed here called "supernova twinning" doubles the accuracy of the measured distances and will provide a well-calibrated, precision sample for probing the universe's expansion history.

Berkeley Lab's role in charting the large-scale structure of the universe began in 2005, when we proposed and led the Baryon Oscillation Spectroscopic Survey (BOSS) experiment, establishing baryon acoustic oscillations (BAO) as a precision technique to explore the effects of dark energy. Following the success of the BOSS and follow-on eBOSS (Extended Baryon Oscillation Spectroscopic Survey) experiments, we proposed and led the design and construction of the first Stage-IV dark energy experiment, DESI, on the Nicholas U. Mayall Telescope at Kitt Peak National Observatory. DESI is on its way to creating the largest 3D map of the universe. This map will include 14 million bright galaxies, 7 million luminous red galaxies, 16 million emission line galaxies, and 3 million quasars, which combined span most of cosmic time. The cosmology results from the first year of data were announced in 2024. They exceed the precision from all previous such maps and, combined with CMB data, provide intriguing hints for dark energy varying with time. These results will continue to improve with analyses of the DESI three-year dataset and a final dataset at the end of the program in 2026 or 2027.

FIVE-YEAR GOALS

- Complete DESI survey and publish world-leading results on dark energy and its evolution over cosmic time.
- Design DESI-2 survey and continue R&D for a Stage 5 spectroscopic survey.
- Advance design of a stage-IV CMB experiment to study primordial inflation.

TEN-YEAR GOALS

- Perform observations for the DESI-2 survey and finalize design of a Stage 5 spectroscopic survey.
- Construct a stage-IV CMB experiment to study primordial inflation.

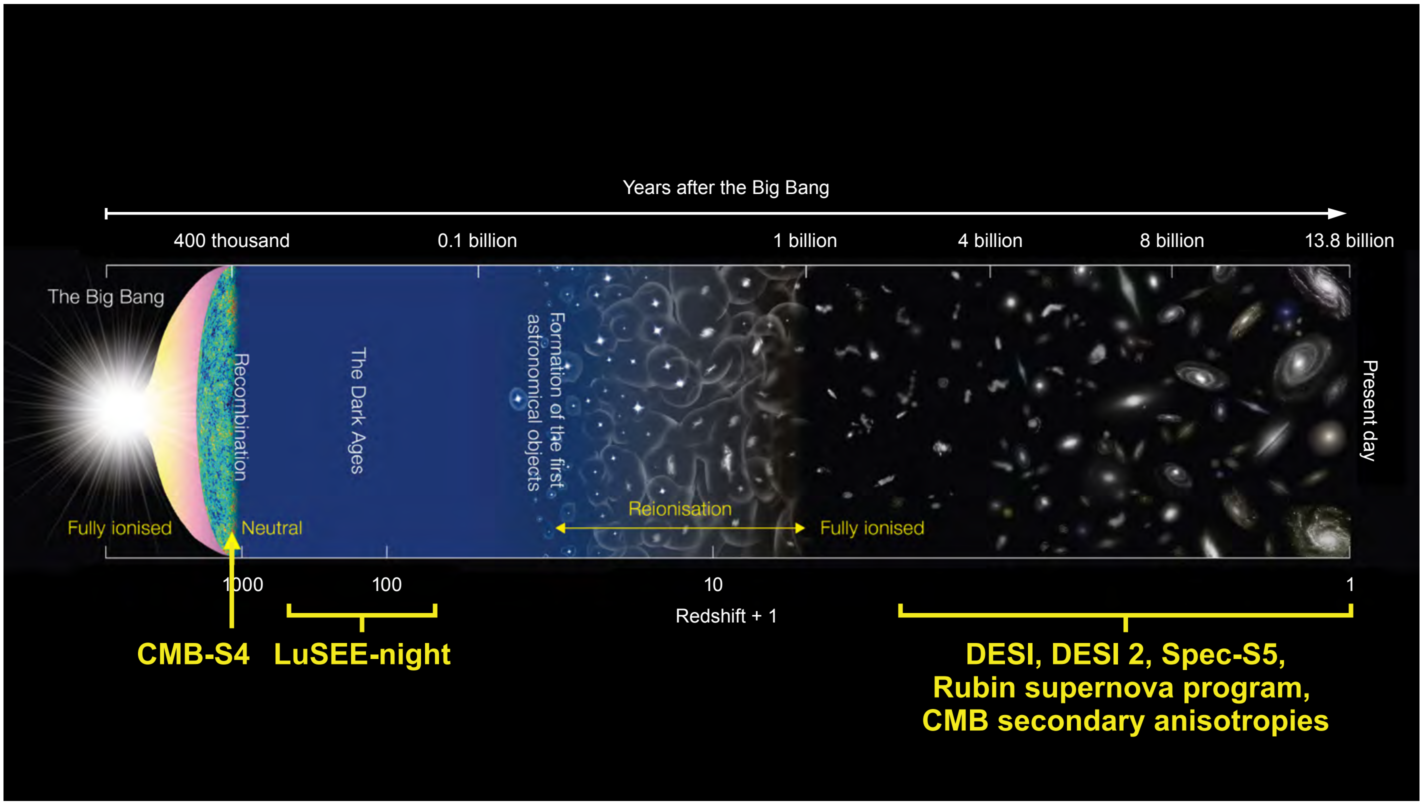
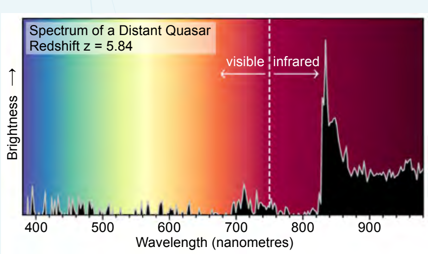


Diagram depicting the major milestones in the universe's evolution and the Berkeley Lab projects projects that explore each epoch of its history. *Illustration credit: David Schlegel, Berkeley Lab. Background image credit: National Astronomical Observatory of Japan (NAOJ)*

The DESI-2 program has been recommended by the 2023 P5 Report as "the first step at going beyond the galaxy surveys constructed as a result of the previous P5 report." DESI-2's scientific goals include constraining cosmic acceleration by extending the DESI dark energy constraints deeper in the matter-dominated regime, providing 5%-level constraints on the dark energy density at epochs when the standard cosmological model predicts that dark energy is only a few percent of the total energy density of the universe. The combination of Rubin imaging and DESI-2 spectroscopy will enable additional tests of the cosmological paradigm. This DESI-2 program will require servicing and upgrades of the DESI instrumentation, specifically targeting the robotic focal plane and the charge-coupled devices (CCDs) detector arrays. The DESI-2 program includes an ambitious imaging survey in customized blue filters for selecting a sample of high-redshift galaxies at high completeness and purity.

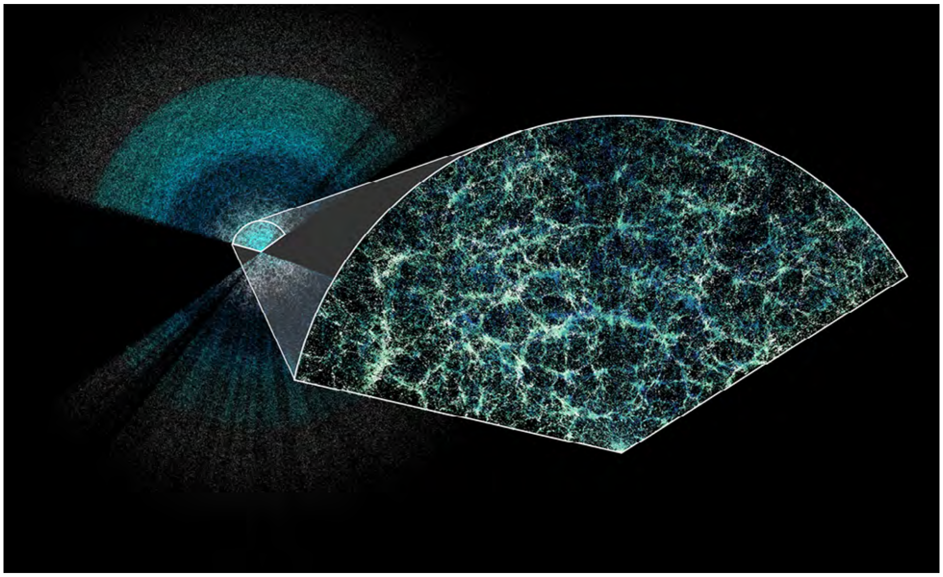
Berkeley Lab has developed concepts for a next-generation spectroscopic survey, Spec-S5. This concept has been endorsed by P5 to "advance our understanding and reach key theoretical benchmarks in several areas: inflationary physics via the statistical properties of primordial fluctuations, late-time cosmic acceleration, light relics, neutrino masses, and dark matter." The combination of CMB-S4 and Spec-S5 in the 2030s will lead to improved understanding of early universe cosmic inflation, with Spec-S5 mapping more linear modes of the early universe than are possible from CMB experiments. The details of the scientific goals and requirements will be informed by the results from DESI and Rubin Observatory.



DESI spectrum of a quasar at a distance of 12.3 billion light-years, near the limit of the observable universe. The universe's expansion has stretched the light's wavelength and shifted it into the infrared. *Credit: Eleanor Downing/DESI Collaboration*

DESI is installed on the Nicholas U. Mayall 4-meter Telescope at Kitt Peak National Observatory near Tucson, Arizona. *Credit: Marilyn Chung, Berkeley Lab*

The Spec-S5 R&D program over the next five years will develop the necessary instrumentation, refine the survey approach, and design the necessary pre-imaging. One key area of development is fiber robot positioners, miniaturized to a center-to-center spacing of 6 mm such that Spec-S5 will be multiplexed with 25,000 fibers simultaneously observing that many targets in the sky. Should budgets allow, the goal is to demonstrate the necessary technologies and establish agreements for the necessary telescope platforms such that Spec-S5 could enter construction before the end of the decade and begin operations at the conclusion of DESI-2.



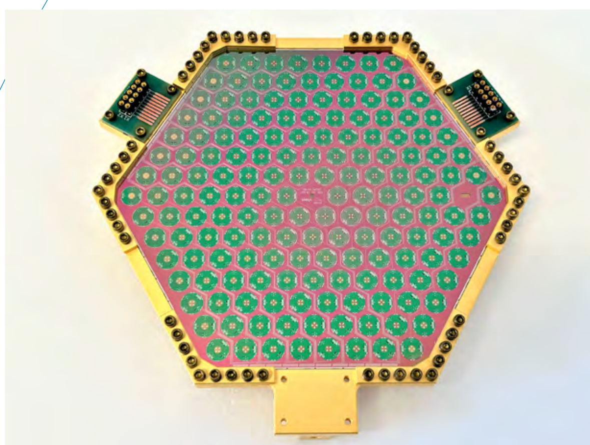
DESI has made the largest 3D map of our universe to date. Earth is at the center of this thin slice of the full map. The underlying structure of matter in our universe appears clearly in the magnified section. *Credit: Claire Lamman, DESI collaboration (custom colormap package by cmastro)*

3.2.6 UNDERSTAND WHAT DRIVES COSMIC EVOLUTION: COSMIC MICROWAVE BACKGROUND

CMB radiation, the earliest light in the universe, has traveled to us for more than 13 billion years, carrying the fingerprints of the early universe. These "baby pictures" carry a wealth of information about both the early universe and the imprints collected from the journey through the evolving structures of the universe. Precision measurements of the CMB from previous ground and space-based experiments have provided detailed insights into the amount of matter and baryonic matter in the universe, the geometry of space-time, and other fundamental parameters.

The goal of CMB-S4 is to extend these measurements to a new level of precision, including both a wide-scale legacy survey and a smaller, very deep map of polarization patterns. Polarization is the key to detecting the primordial gravitational waves from the era of inflation, when the universe expanded by many orders of magnitude in a fraction of a second. In addition, CMB-S4 will contribute to a broad program of fundamental physics and astrophysical measurements, such as the sum of neutrino masses, dark energy, dark matter, relic particles, and transient phenomena in the microwave sky.

Berkeley Lab has served as the lead lab for CMB-S4 since 2020. We established the CMB-S4 project office, developed detailed construction plans including cost and schedule, and established a partnership with many other labs and universities. Following infrastructure issues that will prevent construction at the South Pole, the team is developing alternative locations to achieve breakthroughs on inflationary science.



CMB detector array for CMB-S4 designed by Berkeley Lab and fabricated at SEEQC, Inc. *Credit: Aritoki Suzuki, Berkeley Lab*

Suvan Ravi (left), a student in UC Berkeley's Undergraduate Research Apprentice Program, and Kaja Rotermund, a Berkeley Lab Physics Division postdoctoral fellow, assemble a scale model of LuSEE-Night payload for an antenna beam characterization test. *Credit: Aritoki Suzuki, Berkeley Lab*

3.2.7 DETECTOR RESEARCH AND DEVELOPMENT AND QUANTUM INFORMATION SCIENCE

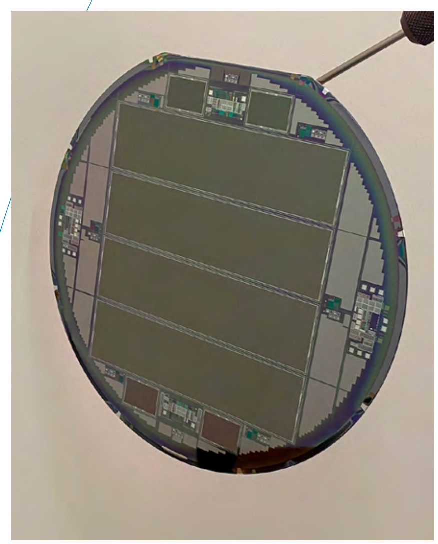
A critical element of Berkeley Lab's leadership in particle physics and cosmology has always been the development of advanced detectors. From the bubble chamber to the time projection chamber originally developed at Berkeley Lab, new detector technologies have been widely adopted beyond their originally intended application. For example, the time projection chamber was conceived as a gaseous vertex-reconstructing instrument for collider physics, and a time projection chamber now forms the core central detector of the cryogenic liquid LZ instrument that is searching for dark matter. Red-sensitive 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 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 detectors at the LHC and the Relativistic Heavy Ion Collider (RHIC). Berkeley Lab also developed bolometers and a frequency multiplexed readout adopted by several CMB experiments

The Physics Division Detector Development Group continues to invest in both incremental and transformational ("blue sky") R&D, targeted at the current and future needs across the DOE Office of Science's Intensity, Energy, and Cosmic Frontiers. New developments in microelectronics are a core component of several of our R&D directions. Many Berkeley Lab-wide resources assist us in these efforts, including the Engineering Division's Integrated Circuit (IC) Design Group, Electronics Design Group, fabrication shops, and Composites Facility; the Molecular Foundry; the Nuclear Science Division's Semiconductor Detector Lab (SDL); and our Microsystems Lab.

R&D focus areas include low-power pixelated readout for large cryogenic time projection chambers (LArPix), novel germanium CCDs for extended infrared spectral sensitivity, new modes of operation for liquid xenon time projection chambers (e.g., crystaLiZe, HydroX), novel materials and readout for TES and MKID (Microwave Kinetic Inductance Device) bolometers and calorimeters, high-channel-count multiplexed readout for CMB and dark matter, 4D tracking pixel chips, and on-chip ML for selective triggering based on pattern recognition. Newer efforts within the division include optomechanical sensors as tabletop, sensitive probes of new physics, and the nanoCMOS (complementary metal-oxide-semiconductor) co-design project for novel wavelength-sensitive photon counting. Learn more about the Physical Science Area's efforts in microelectronics in Section 7.2.

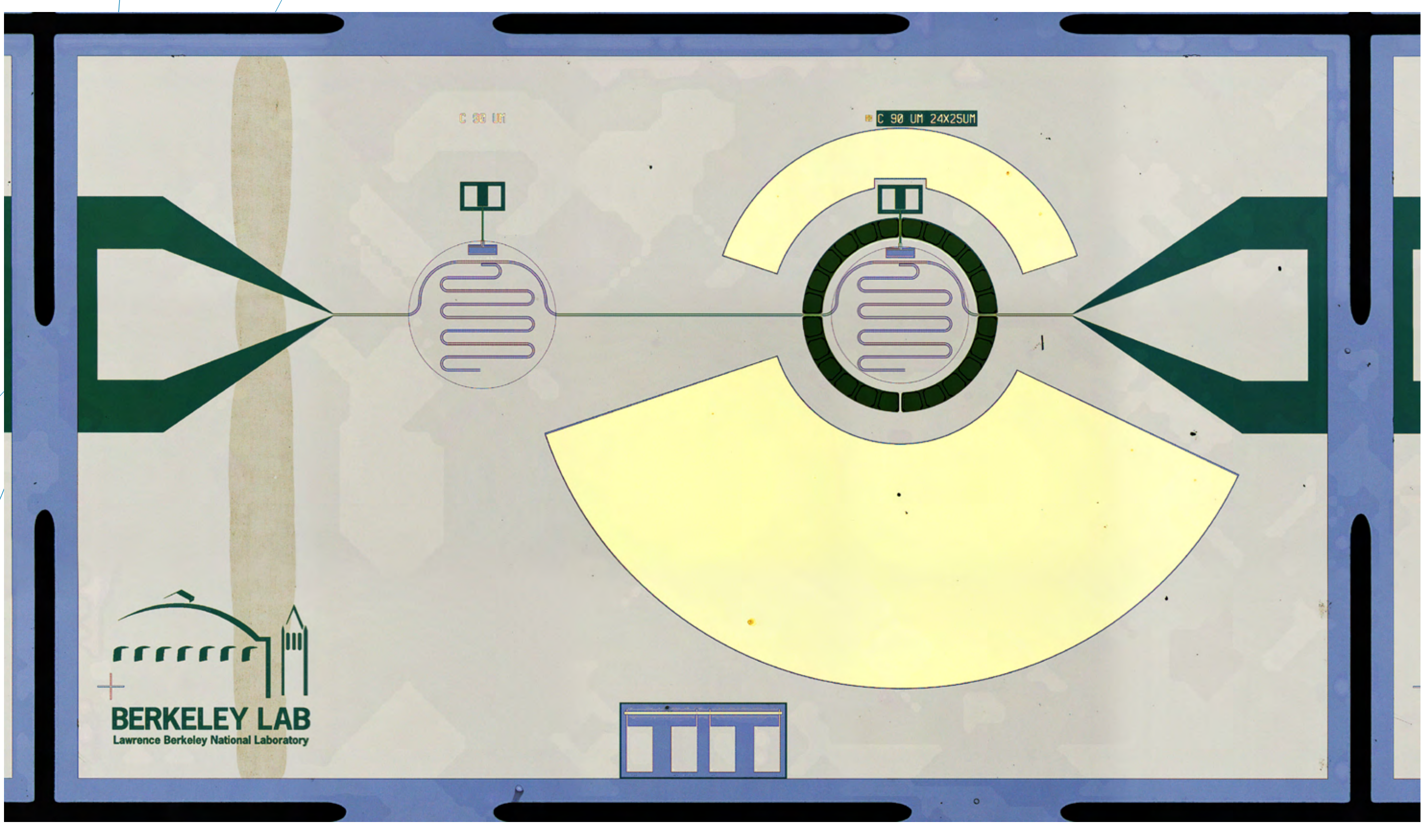
FIVE-YEAR GOALS

- Pursue both incremental and blue-sky R&D.
- Make critical R&D breakthroughs on future detection technologies and techniques.



Skipper CCDs, used at the Southern Astrophysical Research (SOAR) Telescope for astronomical observations, were designed by Berkeley Lab senior engineer Steve Holland. After the CCDs were fabricated at Teledyne DALSA in Canada, they were processed at Berkeley Lab's Microsystems Laboratory. The CCDs are "back illuminated," which makes them highly sensitive to light.
Credit: Steve Holland/Berkeley Lab

The quantum sensors program aims to develop the next generation of sensing technologies for weak signal experiments, in particular to search for particle dark matter and BSM particles and interactions. The program is focused on investigating new sensing technologies that outperform the present state of the art and bringing them to sufficient technical maturity for use in separately funded experiments, such as TESSERACT or future Advancing Science and Technology through Agile Experiments (ASTAE) program experiments, as recommended by P5. This effort is described in detail in Section 3.2.4, "Determine the Nature of Dark Matter." Learn more about the Physical Science Area's efforts in quantum information science in Section 7.3.



Photograph of superconducting resonators isolated by thin silicon nitride bridges to decouple the resonators from environmental noise. Berkeley Lab is designing, building, and testing novel superconducting sensors like MKIDs and TESs. Recent work is focused on novel devices fabricated from hafnium, which have a lower (and tunable) Tc and may have a very high sensitivity. Applications include CMB detection, dark matter searches, and searches for neutrinoless double beta decay.
Credit: Aritoki Suzuki, Berkeley Lab

3.2.8 THEORY

The particle theory group aims to develop groundbreaking new theoretical concepts, methods, and 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 part of the Berkeley Center for Theoretical Physics, a joint research center of the UC Berkeley Physics Department and the Berkeley Lab Physics Division.

Joint theory group/dark matter group discussion on dark matter models.
Credit: Christian Bauer, Berkeley Lab

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 with exceptional strength in a wide spectrum of research directions, in both high-energy experiment and theory. Daily interactions, joint seminars, workshops, and research in a wide area of topics provide a unique 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, in precision lepton and quark flavor physics, and in the search of dark matter through astrophysical observations. The group has also established new research directions in the exciting area of quantum information science, developing novel avenues for using quantum sensors to detect faint interactions of new physics effects with Standard Model particles and new strategies for using quantum computers to simulate the dynamics of gauge theories. These developments will enable theoretical predictions that are out of the realm of possibility for classical computers.

3.2.9 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 Sciences Area, 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 ML that are being intensely applied to the analyses of data from physics experiments. We also formed a new group in the Physics Division, the Machine Learning for Fundamental Physics Group, with strong connections to other divisions at Berkeley Lab and various groups at UC Berkeley, including the Berkeley Institute for Data Science. The group is leading crosscutting research in a number of areas, including simulation-based inference, surrogate modeling, and anomaly detection. Learn more about the Physical Science Area's efforts in advanced computing in Section 7.1, and in quantum computing in Section 7.3.1.

3.2.10 PARTICLE DATA GROUP

The PDG provides a regularly updated authoritative and comprehensive summary of particle physics and related areas of cosmology. The 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. Since 2021, the PDG has been an Office of Science PuRe Data Resource.

As it has for the past 65 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 continuously adapted to new developments in the field. Driven by the needs and wishes of the particle physics community, the RPP is available electronically in different formats, including a first version of a new API for programmatic access. For the time being, the RPP remains available in print as the *PDG Book* and *Particle Physics Booklet*.

FIVE-YEAR GOALS

- Continue the crucial work of the PDG, including the implementation of a new API to make PDG data available in machine-readable format.

In addition to its publication in a scientific journal, the RPP is available in different formats, including (from left to right), the PDG Book, the Particle Physics Booklet, an Android and web app, the interactive pdgLive web application, the main PDG website, and (front center) a new API providing programmatic access to PDG data. *Credit: Paul Schaffner, Berkeley Lab*

A subset of germanium detectors installed for performance tests of the Gamma-Ray Energy Tracking Array (GRETA), the world's most sensitive gamma-ray spectrometer, which will be used at the Facility for Rare Isotope Beams (FRIB) for studies of nuclear structure and nuclear astrophysics. *Credit: Heather Crawford, Berkeley Lab*

4. NUCLEAR SCIENCE

4.1 EXECUTIVE SUMMARY AND STRATEGIC PILLARS

4.1.1 MISSION

The Nuclear Science Division (NSD) supports Berkeley Lab's vision of "bringing science solutions to the world" by leading discovery and innovation in nuclear science and technology.

We advance the understanding of all facets of nuclear matter and forces through experiment and theory. We drive innovation in instrumentation and computing for fundamental research and applications for societal benefits. We inspire and train the next generation of researchers, fostering a vibrant, engaging, and safe environment with opportunities for everyone to thrive.

4.1.2 INTRODUCTION

The NSD at Berkeley Lab conducts basic research to understand the structure and interactions of nuclei and the forces of nature as manifested in nuclear matter, topics that align the division with the national program as elucidated in the 2023 US Nuclear Science Long Range Plan. The NSD also advances nuclear physics applications in radiation detection and imaging, and nuclear data.

The NSD has programs in nuclear structure and dynamics; relativistic heavy-ion and nucleon structure physics; nuclear astrophysics; nuclear theory; neutrino properties; data evaluation; advanced instrumentation; and applied nuclear physics. The NSD also operates the 88-Inch Cyclotron, the home of the Berkeley Accelerator Space Effects (BASE) Facility, and supports a local research program in nuclear science. The NSD exploits new opportunities to enable cutting-edge science, for example through advanced computing, and provides science education for the public and students at all levels.

The NSD engages in collaborative research with domestic and international partners, and benefits from particularly strong links to the departments of Physics and Nuclear Engineering at the University of California, Berkeley (UC Berkeley).

Cover of 2023 NSAC Long Range Plan for Nuclear Science.

2023 NUCLEAR SCIENCE ADVISORY COMMITTEE (NSAC) LONG RANGE PLAN

For more than 40 years, 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. The latest plan, which was released in October 2023 and is entitled *A New Era of Discovery*, identifies opportunities for advancing our understanding of nuclear science and using that science in the service of society. The plan makes four recommendations that prioritize (1) capitalizing on past investments in theoretical and experimental research, (2) leading the expeditious construction of ton-scale neutrinoless double beta decay experiments, (3) completing construction of the Electron-Ion Collider (EIC), and (4) investing in new initiatives to advance discovery science and the application of nuclear science and technology. With its prominent research programs spanning all major areas of nuclear science, leading roles in neutrinoless double beta decay experiments and the EIC, and highly active programs of applied research, the NSD is well aligned with all the major components of this framework and the plan's recommendations.

The NSD's scientific activities are supported by the following strategic pillars:

Science and Discovery. The NSD performs world-leading research in basic and applied nuclear science with crosscutting nuclear theory efforts. The following are our priorities for this pillar:

- Discover and study the phases and structures of strongly interacting matter.
- Explore the boundaries of existence for atomic nuclei and their role in the universe.
- Use nuclear processes to study neutrino properties and beyond the Standard Model (BSM) physics.
- Develop and apply nuclear technologies, methods, and data to address societal needs.
- Exploit advanced research computing for science and technology developments.

Instrumentation and Facilities. The NSD operates the 88-Inch Cyclotron, the Semiconductor Detector Laboratory (SDL), and the Scintillator Engineering Laboratory (SEL). The following are the strategic priorities for this pillar:

- Reinforce the 88-Inch Cyclotron as a national center for heavy-element research and a leading facility for space effects measurement and ion source development.
- Develop novel instrumentation for next-generation experiments supporting the 2023 US Nuclear Science Long Range Plan.
- Make the SDL and SEL engines of innovation and opportunity.

People and Skills. The NSD trains the next generation of leaders in nuclear science and sustains an environment where everyone belongs and can thrive. We collaborate across disciplines and strive to inspire the public through innovative outreach. Activities associated with this pillar are discussed in Section 9.

4.2 SCIENCE AND DISCOVERY

4.2.1 DISCOVER AND STUDY THE PHASES AND STRUCTURES OF STRONGLY INTERACTING MATTER

Quarks and gluons are the fundamental constituents of the nucleons and nuclei that constitute the bulk of visible matter in the universe, and their interactions are governed by quantum chromodynamics (QCD). While QCD is well understood in the high-energy limit, the low-energy regime is driven by emergent phenomena, making analytic calculations nearly impossible. As the low-energy regime governs the formation of matter, understanding the nature of matter in the universe requires the integration of various experimental and theoretical approaches.

The Relativistic Nuclear Collisions (RNC) and Nuclear Theory programs in the NSD have made discoveries about the nature of matter in the early universe (the "hot QCD" regime), the present day (the "cold QCD" regime), and the transition of systems of bare quarks into bound states (hadrons). We advance this forefront research through leadership in key experiments, realizing the needed detectors and analyzing the data using high-performance computing (HPC) and advanced computing techniques, including artificial intelligence (AI) and machine learning (ML).

Previous studies at RHIC and the Large Hadron Collider (LHC) have shown that at sufficiently high temperatures, the quark-gluon plasma (QGP) created in high-energy heavy-ion collisions acts as a perfect liquid. A key remaining question is how matter transitions from the "cold" phase of protons, neutrons, and nuclei to the "hot" phase in heavy-ion collisions, and how this depends on the temperature and density of the system created in the collision. Berkeley Lab scientists lead key studies to understand the nature of this phase transition and search for a QCD critical point, guided by nuclear theory efforts. Beyond understanding this phase transition, probes like heavy flavor quarks can answer questions about the formation and detailed structure of the QGP.

The sPHENIX experiment can identify these heavy flavor states. High-energy showers, or "jets," of quarks and gluons are created when a quark is struck with sufficient energy. These jets can be used to probe the QGP formation and its properties. The high-energy measurements at A Large Ion Collider Experiment (ALICE) will take full advantage of both the jet and heavy flavor measurements.

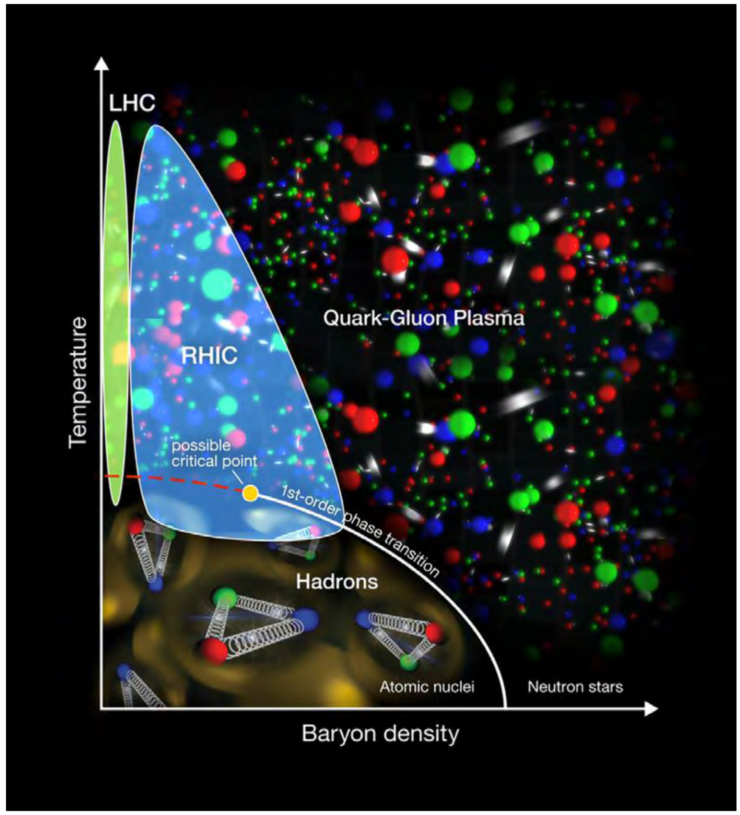
Vast progress has been made in understanding the spatial structure and the momentum distribution of quarks in the proton, but fundamental questions remain. While a proton is often thought of as a system of quarks

FIVE-YEAR GOALS

- Complete the Solenoidal Tracker (STAR) quantum chromodynamics (QCD) phase diagram studies and sPHENIX Heavy Flavor program at the Relativistic Heavy Ion Collider (RHIC).
- Lead a vigorous heavy-ion program focused on heavy flavor jet substructure with ALICE (A Large Hadron Collider Experiment).
- Maintain a vibrant program of experimental leadership at Thomas Jefferson National Accelerator Facility (TJNAF) focused on short-range correlations and structure functions.
- Advance our understanding of QCD matter through a comprehensive theory effort in close collaboration with experiment.
- Build a compelling day-one physics program for the EIC, based on our expertise in heavy-ion and medium-energy physics experiment and theory.
- Lead development and construction efforts for the Silicon Vertex Tracker (SVT) for the Electron-Proton/Ion Collider (ePIC) detector at the EIC

TEN-YEAR GOALS

- Deliver the EIC ePIC SVT detector and support commissioning and operation.
- Take a leadership role in delivering the early EIC physics program and support EIC data-taking and early physics analyses.
- Establish a West Coast theory alliance for EIC physics.
- Make significant contributions to the long-term experimental heavy-ion program at CERN (the European Organization for Nuclear Research).
- Create a cohesive effort around lattice QCD and its applications to symmetries.



A schematic phase diagram of nuclear matter. With experiments at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) and the LHC at CERN, NSD scientists are mapping out the boundaries between the regular nuclear (hadronic) matter and the QGP and are also studying the properties of the QGP. *Credit: Image courtesy of Brookhaven National Laboratory*

bound together by massless gluons, QCD leads to gluons being a significant constituent of the proton, contributing to its mass and spin. Such studies will be further advanced through theoretical studies including Lattice QCD as well as experiments at TJNAF, where the RNC program will also continue to investigate the short-range correlations between nucleons. In the longer term, the EIC will provide unique new insights into the structure of matter. The EIC will employ electron-proton and electron-ion collisions to open new frontiers in the study of dense gluon matter, as well as in nucleon and nuclear tomography, enabling multidimensional maps of the structure inside nucleons. The RNC and Nuclear Theory Programs have had long-term roles in developing the physics case and needed capabilities for the EIC, and the RNC has a leading role developing the SVT, the central piece of the Electron-Proton/IonCollider (ePIC) detector at the EIC.

4.2.2 EXPLORE THE BOUNDARIES OF EXISTENCE FOR ATOMIC NUCLEI AND THEIR ROLE IN THE UNIVERSE

Atomic nuclei comprise 99.9% 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. Which combinations of protons and neutrons can combine to form a bound nucleus and what features emerge in these nuclei are intriguing questions at the heart of nuclear structure and reactions studies. They motivate exploration of the nuclear landscape's limits and provide stringent tests of our understanding of nuclei and the underlying forces. The NSD has a vibrant program studying nuclear structure, with a focus on exotic nuclei, especially those with the largest neutron or proton excess or the heaviest masses.

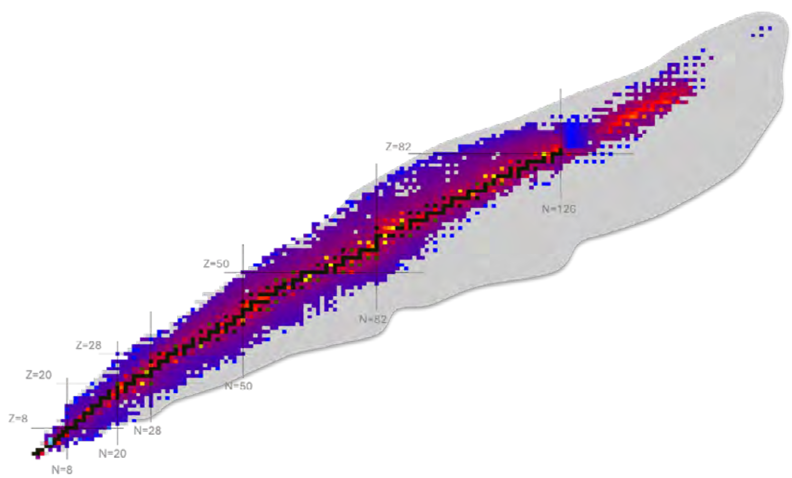


Chart of nuclides showing the nuclear landscape through the number of neutrons (N) and protons (Z) in the nucleus. Known nuclides are shown as colored squares, and the hypothesized area where nuclei are bound is indicated in grey. Beyond the east and west borders, the nucleon driplines, nuclei are unstable. To the north, the strong force can no longer overcome the Coulomb repulsion by the protons, setting the limits of the heaviest (superheavy) nuclei. *Credit: Heather Crawford, Berkeley Lab*

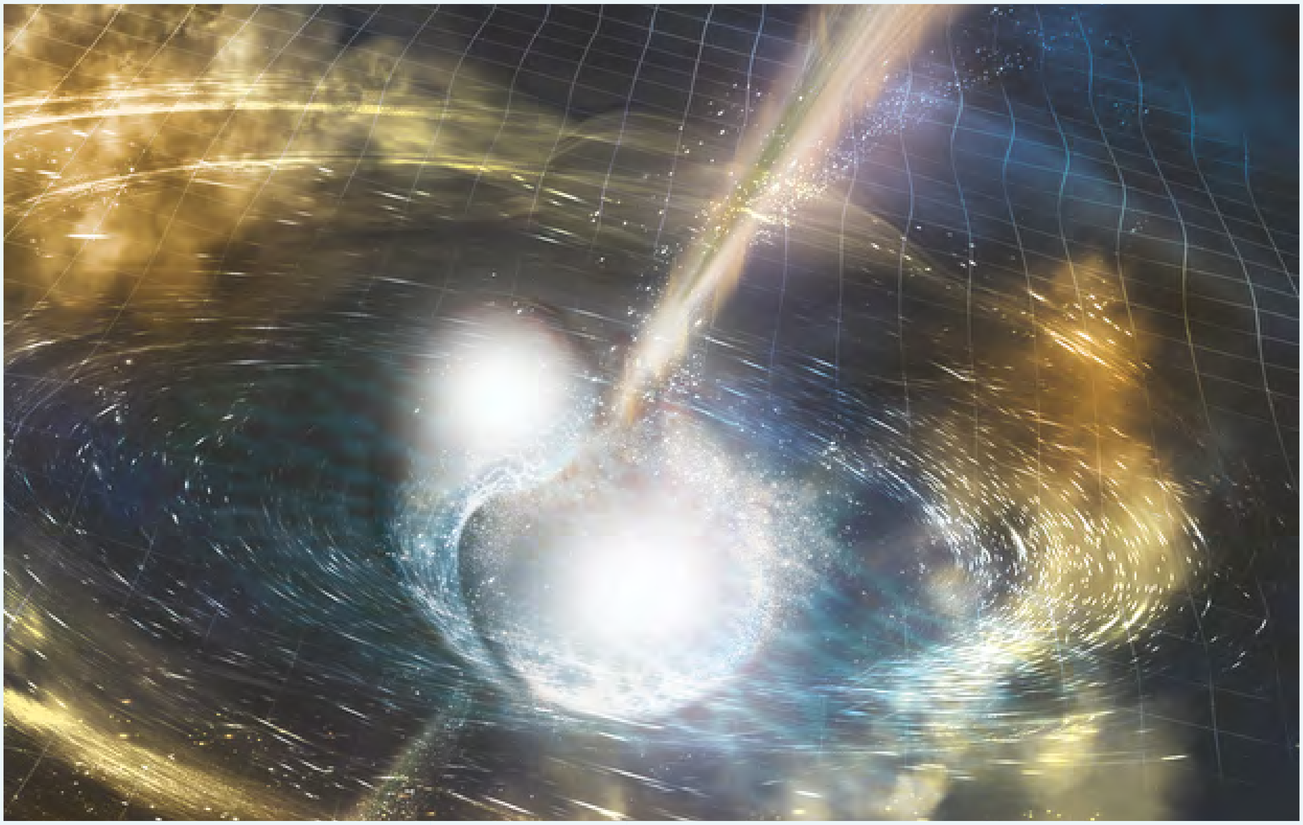
The study of the heaviest elements by Berkeley Lab scientists dates to the Lab's beginnings and has resulted in the discovery of 14 transuranium elements. Today, the high-intensity beams from the 88-Inch Cyclotron combined with world-class instrumentation provide a unique opportunity to determine the properties of the heaviest elements and to establish the limits of their existence and their structure. A major activity in the next several years will be to synthesize and study superheavy elements with a goal of a new element (Z=120) discovery. The study of

FIVE-YEAR GOALS

- Complete the Gamma-Ray Energy Tracking Array (GRETA) project and deliver it to the Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU).
- Carry out a leading research program with GRETA and maintain technical leadership in future developments.
- Maintain a visible program at FRIB with clear scientific and technical leadership building on GRETA.
- Initiate nuclear theory research efforts in nuclear astrophysics and nuclear structure.
- Synthesize and study superheavy elements with a goal of a new element (Z=120) discovery.
- Carry out high-fidelity simulations of astrophysical explosions to elucidate heavy-element nucleosynthesis.

TEN-YEAR GOALS

- Constrain cosmic nucleosynthesis and the nuclear equation of state (EoS) by integrating results from FRIB into astrophysical simulations for comparisons with data from multi-messenger astronomy.
- Maintain a visible and leading scientific program at FRIB to understand the structure and properties of the most exotic nuclei.
- Expand the scope of heavy-element research at the 88-Inch Cyclotron, building on the new capabilities for mass and laser spectroscopic studies and for measurements of chemical properties.



Artist's illustration of two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the bursts of gamma rays shot out just seconds after the gravitational waves. Swirling clouds of material ejected from the merging stars are also depicted. The clouds glow with visible and other wavelengths of light.
Credit: NSF/LIGO/Sonoma State University/A. Simonnet

NUCLEAR THEORY COMPUTING

Most atomic nuclei are created in the interiors of stars, during stellar explosions, or through neutron star mergers. They are also used as laboratories for searching for new physics, such as neutrinoless double beta decay of medium and large nuclei, or dark matter particles scattering off nuclear targets. The strong nuclear force, which binds nucleons into nuclei, is a relatively small residual force that emerges from QCD and encodes the fundamental interactions between the quarks and gluons that bind into protons, neutrons, and other states of strongly interacting matter. Understanding nuclear physics at each of these disparate scales requires the use of complex, nonperturbative methods, such as Lattice QCD, that leverage HPC with state-of-the-art software that can efficiently use modern, heterogeneous architectures, such as Perlmutter at Berkeley Lab's National Energy Research Supercomputing Center (NERSC). Members of the Nuclear Theory Program are engaged in these various aspects of computational nuclear physics, working with and leading multi-institutional teams on both the science and development of the software. A post-exascale question we hope to answer is how to quantitatively connect our understanding of dense nuclear environments in neutron stars to the fundamental quark and gluon degrees of freedom of QCD.

key chemical and atomic properties of heavy nuclei will continue in collaboration with the Chemical Sciences Division and UC Berkeley.

The properties of excited states in neutron-rich nuclei can reveal a great deal about their structure and the forces between the nucleons. NSD scientists continue to pioneer high-resolution gamma-ray detector technologies, one of the most powerful techniques to study excited states in nuclei, and their applications. Berkeley Lab designed and built one of the world's most advanced gamma-ray detector arrays, GRETINA, which uses the gamma-ray energy tracking technology developed at Berkeley Lab.

Engineering drawing of GRETA, which will be a key instrument at FRIB at MSU.
Credit: Heather Crawford, Berkeley Lab

We are currently completing the gamma-ray tracking array GRETA, a 4π array of highly segmented high-purity germanium (HPGe) detectors, the world's most sensitive gamma-ray spectrometer. GRETA will be a key instrument for FRIB's science program in nuclear structure and nuclear astrophysics. Berkeley Lab researchers will use GRETA to study the most weakly bound systems accessible. A program of precision mass measurements of exotic nuclei is underway at both FRIB and the 88-Inch Cyclotron for nuclear structure and nuclear astrophysics.

The cosmic production of the heavy elements occurs within stars and stellar explosions along nuclear pathways that often proceed far from stability. Understanding the origin of the elements requires a coordinated effort between nuclear experiments that determine the properties of rare isotopes and key reaction rates, and astrophysical simulations that can specify the astrophysical environments within which heavy-element nucleosynthesis takes place, such as core collapse supernova explosions of massive stars, or mergers of neutron stars. Characterizing the conditions in these systems requires multiphysics simulations of the coupled evolution of magnetohydrodynamics, nuclear kinetics, the EoS of dense matter, transport of neutrinos and photons, and a general-relativistic description of gravity.

Berkeley Lab scientists have developed sophisticated software ecosystems for modeling the complex dynamics of supernovae, mergers, and related explosive phenomena exploiting advances in HPC (e.g., exascale machines). The codes generate synthetic observables that are compared with experimental data to validate the simulations and constrain nuclear physics.

Experimental efforts by NSD scientists will complement the theoretical work by extracting observables and understanding their impact on nucleosynthesis dynamics through quantification of nuclear data uncertainties into uncertainties on astrophysical model predictions.

Researchers install tellurium oxide (TeO_2) crystals in the CUORE experiment at Laboratori Nazionali del Gran Sasso in Italy. These crystals are cooled to below 20 mK during operation. The CUPID experiment will use 100Mo-enriched lithium molybdate crystals in the same cryogenic infrastructure. *Credit: Courtesy of CUORE Collaboration*

4.2.3 USE NUCLEAR PROCESSES TO STUDY NEUTRINO PROPERTIES AND SEARCH FOR PHYSICS BEYOND THE STANDARD MODEL

Neutrinos are the lightest-known and most abundant matter particles in the universe. In the Standard Model of particle physics (SM), neutrinos were originally postulated to be massless. Berkeley Lab's NSD played leading roles in two pioneering experiments—Sudbury Neutrino Observatory (SNO) and KamLAND—which demonstrated neutrino flavor transformation and hence, nonzero neutrino mass. Along with the Daya Bay Reactor Neutrino Experiment led by researchers from Berkeley Lab's Physics Division, these experiments set the directions of neutrino research.

While researchers in the Physics Division are aiming to understand the charge-parity properties of neutrinos, scientists in the NSD are leading efforts to determine if neutrinos are their own antiparticles. Both efforts would shed light on the fundamental issue of matter-antimatter asymmetry, or why there is matter but not antimatter all around us.

To this end, NSD scientists are searching for the SM-forbidden neutrinoless double beta decay process in several isotopes, including 76Ge in the just-completed Majorana Demonstrator and the future Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay (LEGEND), 130Te in the operating CUORE and SNO+ experiments, and 100Mo in the planned CUPID experiment. These experiments directly align with the recommendations of the NSAC Long Range Plan for a multi-isotope neutrinoless double beta decay campaign.

Although neutrino oscillation experiments show that neutrinos have mass, they do not determine the absolute value of neutrino masses, only their mass differences. NSD scientists are participating in the KATRIN experiment, aiming to determine the electron neutrino mass through direct kinematic measurement of tritium decay.

FIVE-YEAR GOALS

- Harvest the physics from the current experiments — Cryogenic Underground Laboratory for Rare Events (CUORE), Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay (LEGEND-200), SNO+ (successor to the Sudbury Neutrino Observatory), and the Karlsruhe Tritium Neutrino Experiment (KATRIN) — to establish new limits on the mass and nature of the neutrino.
- Begin construction of "ton-scale" neutrinoless double beta decay experiments by leading R&D for the US CUORE Upgrade with Particle IDentification (CUPID) experiment and providing key components to LEGEND-1000.
- Develop technologies for future measurements in neutrino mass and neutrinoless double beta decay.

TEN-YEAR GOALS

- Complete the construction of CUPID and LEGEND that will target the inverted mass-ordering.
- Demonstrate the scientific impact and technical viability of the Theia detector and lead its future beyond the ton-scale science program.

FIVE-YEAR GOALS

- Establish leadership in multisensor networks for basic and applied science.
- Re-establish technical leadership in biomedical imaging.
- Establish a leading research program in radiation detection and instrumentation for ultrafast timing.
- Realize the full potential of Scene Data Fusion, including advanced robotics and visualization.
- Develop an integrated Berkeley Lab–UC Berkeley nuclear data program, combining the capabilities of the cyclotron with student training to serve national nuclear data needs.

TEN-YEAR GOALS

- Maintain the Applied Nuclear Physics (ANP) Program at the forefront of radiation detection research and applications.
- Expand research in medical physics.

4.2.4 DEVELOP AND APPLY NUCLEAR TECHNOLOGIES, METHODS, AND DATA TO ADDRESS SOCIETAL NEEDS

The Applied Nuclear Physics (ANP) Program develops concepts and technologies that address outstanding questions in basic and applied research, as well as national security and biomedical imaging. At the core are developments of new radiation detection and imaging techniques, sensor fusion, and data analytics concepts and data management.

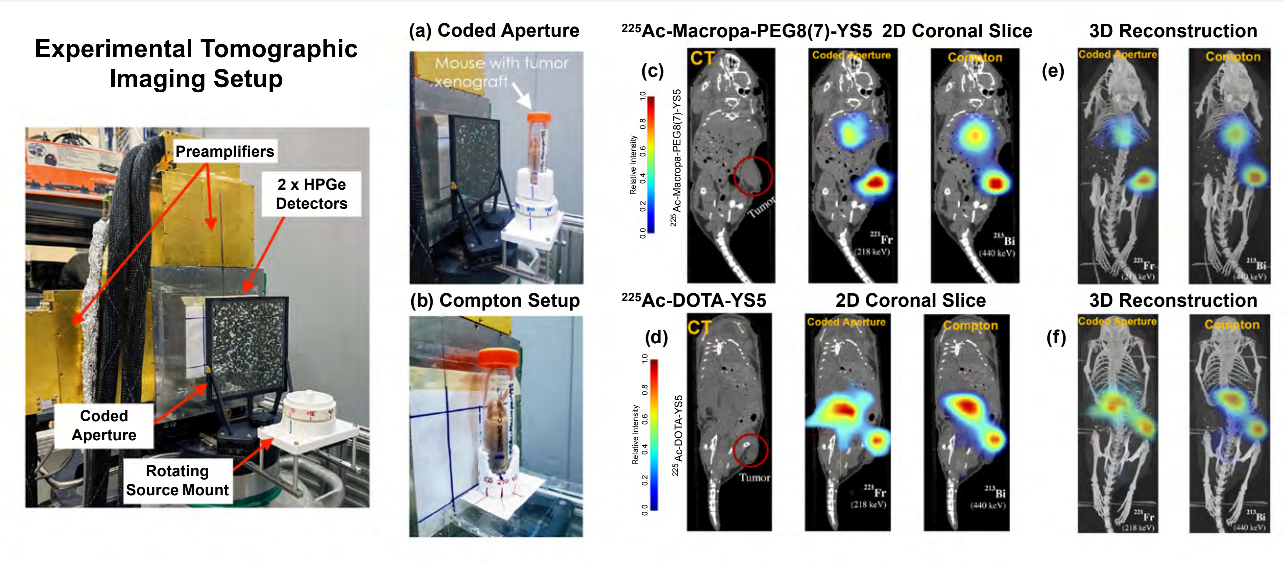
Over the last 10 years, the ANP Program has established itself as a world-leading research program driving new concepts in radiation detection and imaging in data fusion and in deploying such systems in complex environments, including Fukushima in Japan, Chernobyl in Ukraine, and nuclear facilities in the US. The ANP Program plays leadership roles in developing multisensor systems and deploying them on mobile platforms for radiological mapping, and in city-wide static networks to enhance nuclear security. A core technology developed by the ANP Program is the scene data fusion (SDF) concept, which combines radiation detectors with auxiliary sensors such as video, Lidar, GPS, and inertial measurement units to enable free-moving radiation imaging and mapping in real time. More generally, the ANP Program has pioneered using contextual sensing and robotics to enable new and improved capabilities for radiation detection and imaging.

An important aspect in enhancing detection capabilities in complex urban environments beyond the deployment of advanced multisensor systems is state-of-the-art data analytics methodologies such as AI/ML. Interpretable and explainable ML methodologies are of particular interest. We are also adopting advanced computer vision technologies to realize the full potential of multisensor systems and to enable new means for augmented reality (AR) and virtual reality (VR) visualization and control. Some of these technologies are being commercialized and adopted in other countries.

In parallel, the ANP Program explores creating new radiation detector materials in the SEL, and developing and fabricating semiconductor detector systems at the SDL. Details are provided in "Instrumentation and Facilities" (Section 4.3)

Over the next 5 to 10 years, established capabilities and advances will be used to maintain a world-leading research program and to drive applications with a broad impact on society. Particular focus will be on biomedical imaging, ultrafast timing, the full exploration of multisensor fusion concepts such as SDF, and the continued development, deployment, and full utilization of multisensor networks. Unique detector fabrication facilities such as the SEL and SDL will also remain an integral part of our efforts to enable new technologies and scientific discoveries.

The Bay Area Nuclear Data (BAND) Group works to identify and address the nuclear data needs for basic and applied nuclear science and engineering while



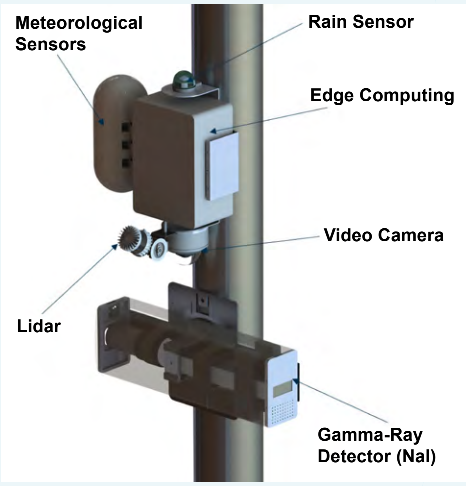
Combined Compton and coded aperture imaging system based on HPGe double-sided strip detectors (left) piloted to develop a high-sensitivity pre-clinical imager to aid in developing 225Ac-labeled therapeutic agents. The images on the right-hand side show results of using this system to image 225Ac agents in a mouse. *Credit: Emily Frame, UC Berkeley*

THE FUTURE OF BIOMEDICAL IMAGING: FLASH RADIOTHERAPY, ION CANCER VERIFICATION, AND TARGETED ALPHA THERAPY

The ANP Program is developing novel instruments and methods for medical and molecular imaging. One major thrust is advanced detector technologies and techniques that aim to more than double the effective sensitivity of positron emission tomography (PET) relative to commercial systems. The ultimate goal is to develop imaging systems capable of real-time, three-dimensional dynamic PET and pharmacokinetic modeling of radiotracers. A second research theme focuses on dose verification for high relative biological effectiveness (RBE) oncologic radiotherapies: precision treatments that allow clinicians to explore improved outcomes and therapeutic endpoints with lower radiotoxicity in healthy tissues and reduced associated side effects. ANP researchers are developing imaging instrumentation for in vivo dose verification in ion cancer therapies and targeted radiotherapeutics building upon the NSD's expertise in radiation detector innovation.

training the next generation of scientists and engineers. The group's activities include both evaluation (which entails theory-guided modeling) and targeted measurements using local, domestic, and international research facilities.

The wide-ranging evaluation program includes nuclear structure evaluation in support of the Evaluated Nuclear Structure Data File (ENSDF) maintained by the National Nuclear Data Center (NNDC) as well as a host of unique databases targeting applications with high societal impact.



Engineering drawing of a multisensor radiation detection system, developed in collaboration with Argonne National Laboratory and fielded as part of a city-scale wireless sensor network. *Credit: Victor Negut, Berkeley Lab*

MULTISENSOR NETWORKS

Researchers in the ANP Program are developing intelligent, multisensor networks to provide new capabilities for field science, nuclear safety, and nuclear nonproliferation. The Platforms and Algorithms for Networked Detection and Analysis (PANDA) project, led by Berkeley Lab in collaboration with the Domain Aware Waggle Network (DAWN) project from Argonne National Laboratory, has developed a network of sensor systems that can provide city-scale radiological/nuclear detection. This system combines gamma-ray detectors with contextual sensors, such as video, Lidar, and meteorological sensors, and performs real-time data analysis and data fusion using state-of-the-art edge and cloud computing capabilities. Ongoing and future work in this area includes developing more advanced data fusion algorithms, exploring new contextual sensing modalities, and designing methods for sensor adaptation and optimization. Examples include collaborations with researchers from Berkeley Lab's Energy Sciences Network (ESnet) and the Earth and Environmental Sciences Area (EESA) to explore mmWave radar for environmental sensing and 5G telecommunications for low-latency, adaptive networking.

Unlike other branches of the US Nuclear Data Program (USNDP), the BAND Group also performs an equally varied measurement program. The primary tool for these experiments is the 88-Inch Cyclotron. Experimental activities include measurements of energetic charged particle-induced cross sections using the stacked target technique. These measurements have, for example, helped to optimize production of the alpha-therapeutic radionuclide 225Ac, which has shown significant promise in treating cancer.

FIVE-YEAR GOALS

- Deploy AI/ML techniques to optimize and control experimental systems and novel analysis approaches for experimental data.
- Demonstrate a new capability for the direct, low-latency integration of detector readout into HPC over wide area networks.
- Develop new Bayesian uncertainty quantification methods for basic and applied nuclear science.
- Continue to exploit advances in contextual sensing, perception, and ML/AI for enhanced radiation detection and imaging.

4.2.5 LEVERAGE ADVANCED RESEARCH COMPUTING FOR SCIENCE AND TECHNOLOGY DEVELOPMENTS

State-of-the-art computational methods and technologies accelerate discovery and enable new and improved capabilities in applied nuclear science. NSD scientists work together with colleagues across the Physical Sciences and Computing Sciences Area to advance the use of AI/ML techniques (see Section 7.1). Specifically, NSD researchers employ advanced computational techniques to analyze complex experimental data, leverage HPC to execute large-scale numerical simulations, and exploit advances in compact edge computing to allow the deployment of advanced data processing algorithms in the field.

NSD scientists use AI/ML methods to optimize and design novel observables of QCD processes for current and future collider experiments, enhancing their sensitivity to phenomena of interest. The application of physics-driven ML models enables the creation of computationally efficient simulations and guides experimental programs at RHIC, LHC, and the future EIC. Similar approaches can be applied to experiments at TJNAF and FRIB. We are utilizing large-scale graphics processing unit (GPU) resources at HPC systems for AI/ML projects and for novel analyses of collider data.

We are using AI/ML methods to enable the automatic optimization and control of experimental systems, including the VENUS ion source (Versatile electron cyclotron resonance [ECR] ion source for NUclear Science) and large detector arrays such as GRETA. We are also developing Bayesian inference and uncertainty quantification methods for use in neutrino physics, heavy-ion physics, and radiological contamination mapping, and are leveraging state-of-the-art neural networks for multimodal data fusion and radiological anomaly detection.

NSD scientists are developing software tools that enable the new generation of leadership class HPC facilities to be used for computational nuclear physics, including nuclear astrophysics simulations and lattice QCD calculations. NSD theorists leading the exascale computing project ExaStar will continue developing nuclear astrophysics simulations with a renewed DOE Scientific Discovery through Advanced Computing Program (SciDAC) project hosted at Oak Ridge National Laboratory. The Lattice Quantum Chromo-Dynamics Project, which is supported by DOE's Nuclear Physics Program and Advanced Scientific Computing Research Program and involves scientists from other national laboratories, including TJNAF, Oak Ridge National Laboratory, Brookhaven National Laboratory, and Los Alamos National Laboratory, supports advances in lattice QCD.

We are developing a distributed experimental data pipeline where experimental electronics subsystems (e.g., as in GRETA) can be directly interfaced to HPC facilities over wide area networks utilizing DOE's Integrated Research Infrastructure testbed through Berkeley Lab's Energy Sciences Network (ESnet) and DOE's Office of Advanced Scientific Computing Research (ASCR).

Within ASCR, we are collaborating with Berkeley Lab's Applied Mathematics and Computational Research Division (AMCRD) and ESnet to develop self-driving 5G networks exploiting the new wireless technologies and novel complex edge hardware capabilities that can provide connectivity to ESnet, enabling efficient processing of portable radiation detector signals.

4.3 INSTRUMENTATION AND FACILITIES

4.3.1 REINFORCE THE 88-INCH CYCLOTRON AS A NATIONAL CENTER FOR HEAVY-ELEMENT RESEARCH AND A LEADING FACILITY FOR SPACE EFFECTS MEASUREMENT AND ION SOURCE DEVELOPMENT

The 88-Inch Cyclotron is a variable energy, high-current, multispecies cyclotron capable of accelerating ions from protons to uranium. It hosts the nation's leading superheavy element research effort and various nuclear data and space effects testing applications. Since 1961, it has maintained its position as a premier stable-beam facility through periodic upgrades, especially to its ion sources, which have enabled the acceleration of an ever-increasing variety of heavy-ion beams up to and beyond the Coulomb barrier. The current superconducting ion source, VENUS, is one of the world's most powerful ECR ion sources.

The BASE Facility at the 88-Inch Cyclotron supports national security and other US space programs with radiation effects testing by providing heavy-ion cocktail beams, low-energy proton beams, and highly parallel beams with micron resolution (microbeams). Almost all US and many foreign spacecraft and commercial aircraft launched in the past 30 years have had parts tested at the facility.

To further facilitate nuclear data applications with neutron beams, we will develop a plan for accelerating and extracting negative ions (specifically H^- and $2H^-$) from the cyclotron via stripping, which would allow for higher-intensity neutron beams by avoiding the current losses incurred in extracting positive ions.

With the addition of a high-power beryllium neutron breakup target these enhanced neutron production capabilities will serve the evolving needs of the space effects measurement community and may open opportunities for medical isotope production at the 88-Inch Cyclotron.

In a joint effort between NSD and the Accelerator Technology & Applied Physics (ATAP) Division, Berkeley Lab is actively developing the next generation of ECR ion sources, using new superconducting materials and new geometries to generate the magnetic fields necessary to control the plasma of ions and electrons. One example is the Mixed Axial and Radial field System (MARS) magnet concept. It replaces six racetrack coils with a single closed-loop coil. Such ion source developments will keep the 88-Inch Cyclotron at the forefront of basic nuclear science and nuclear data research for applications in medicine, nuclear energy, and national security, and will improve the simulation of space effects for satellite components.

FIVE-YEAR GOALS

- Establish the 88-Inch Cyclotron as a national and international center for heavy-element science.
- Position the 88-Inch Cyclotron as a key provider of nuclear data needed to enable and support national activities in energy, medicine, and security.
- Maintain the 88-Inch Cyclotron as a leading facility for space effects measurements needed to support the US government and commercial space and aeronautics communities.
- Develop world-leading ion sources.

TEN-YEAR GOALS

- Complete the MARS-D ion source and install it at the 88-Inch Cyclotron.
- Establish a neutron beam capability for space effects measurements by building a dedicated neutron beam solution for the BASE Facility.

In addition to the scientific program at the 88-Inch Cyclotron, various infrastructure improvement and facility modernization projects are underway with financial support from the DOE Office of Science Nuclear Physics Program and Department of Defense Test Resource Management Center, and institutional support from Berkeley Lab.

4.3.2 DEVELOP NOVEL INSTRUMENTATION FOR NEXT-GENERATION EXPERIMENTS IN SUPPORT OF THE NUCLEAR SCIENCE LONG RANGE PLAN

Berkeley Lab has a long history of developing advanced radiation detectors and associated electronics, and the NSD continues to develop instrumentation for major nuclear physics experiments to support the NSAC Long Range Plan. We produced the neutron transmutation doped sensors for the CUORE experiment, and will produce similar sensors for the CUPID experiment. Low-noise, low-background electronics for the MAJORANA DEMONSTRATOR were developed at Berkeley Lab, and we are currently developing a low-noise, cryogenic application-specific integrated circuit (ASIC) to read out for the LEGEND experiment. We are also exploring the use of graphene field-effect transistors for the read out of HPGe detectors and as novel photosensors.

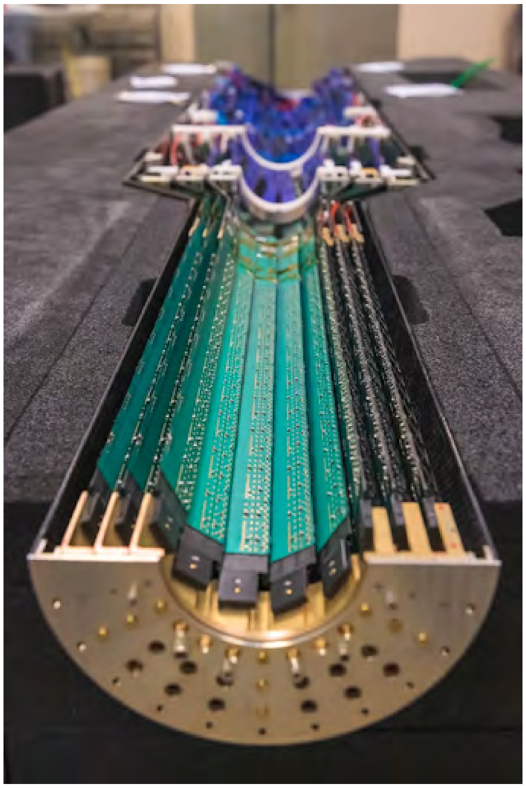
Left to right, Nicole Apadula, a research scientist, Marco McGee Toledo, a mechanical engineer technician, and Eric Anderssen, a staff scientist/engineer, apply a thin layer of coating to one of the corrugated panels that will be installed in the ePIC detector.
Credit: Thor Swift/Berkeley Lab

FIVE-YEAR GOALS

- Demonstrate hybrid Cherenkov and scintillation light technology for neutrino detection with Eos.
- Maintain leadership in advanced gamma-ray detection technology through development of ultrahigh-rate germanium detector systems.
- Develop a baseline conceptual design of the endcap discs for the ALICE 3 detector upgrade.

TEN-YEAR GOALS

- Stay at the forefront of instrumentation development for fundamental and applied nuclear science using the unique capabilities and expertise at Berkeley Lab.



Half barrel of the sPHENIX MTVX detector during assembly at Berkeley Lab.
Credit: RNC Photo Archive, Berkeley Lab

Berkeley Lab has a history of innovative detector development and construction, with an emphasis on silicon tracking detectors in recent years. NSD scientists constructed two half barrels of MAPS (Monolithic Active Pixel Sensors) for the sPHENIX MAPS-based Vertex Detector (MVTX), and led the ALICE-USA part of ITS2 (ALICE's inner tracker system 2, an upgrade of an existing ALICE subsystem). NSD is also involved in developing a new silicon vertex detector, ITS3, for the ALICE experiment. We plan to adapt its technologies to the SVT for the EIC detector ePIC as well as to the future program with ALICE, in particular the endcap discs for the outer tracker of the proposed ALICE 3 detector. We also leverage our ePIC involvement to advance AC-coupled Low Gain Avalanche Diode (AC-LGAD) and MAPS technologies. Aside from leveraging the Engineering Division's expertise and infrastructure, these projects also use the 88-Inch Cyclotron and Berkeley Lab Laser Accelerator (BELLA) Center for timing and tracking studies.

Berkeley Lab has decades of experience in the development of advanced HPGe detectors and gamma-ray spectrometers such as Gammasphere, GRETINA, and GRETA. Future developments of novel gamma-ray detection technologies include ultrahigh count-rate HPGe detectors, ASIC-based readout schemes, and advanced signal processing methods. Such detectors can be deployed as gamma-ray tracking instruments close to the target position at radioactive beam facilities or in the study of superheavy elements.

NSD scientists are also investigating the potential of experimental techniques to search for neutrinoless double beta decays beyond ton-scale experiments. One such experiment is the Theia experiment, proposing to load up to 100 kilotonne of liquid scintillator with 130Te. Novel technology allows simultaneous, or "hybrid," detection of both Cherenkov and scintillation signatures. The NSD has built a prototype, Eos, as a technology demonstrator to test the functionalities of hybrid neutrino detection in neutrino charge-parity violation (CP-violation) and neutrinoless double beta decay experiments, as well as its utility in nonproliferation nuclear-reactor monitoring.

4.3.3 MAKE THE SEMICONDUCTOR DETECTOR AND SCINTILLATION ENGINEERING LABS ENGINES OF INNOVATION AND OPPORTUNITY

The SDL and SEL are leading facilities for developing novel radiation detector technologies. The SDL has pioneered HPGe and cadmium zinc telluride (CZT) detectors. The SDL is currently producing advanced HPGe detectors for the next-generation gamma-ray telescope, the Compton Spectrometer and Imager (COSI), a NASA mission to be launched in 2027 aiming to study stellar evolution and nucleosynthesis in the Milky Way.

The SDL is developing and fabricating a new generation of 3D-position sensitive HPGe detectors that can maintain high-energy resolution at unprecedented count rates. These detectors can enable new capabilities for in-beam nuclear spectroscopy studies of heavy elements at the 88-Inch Cyclotron, the monitoring of burn-up in nuclear reactors, radiation mapping in nuclear incident scenarios, or biomedical imaging.

The SEL is focused on developing luminescent radiation detector materials, and in the future will explore fundamental energy loss mechanisms to improve the fabrication and performance of scintillation detectors and to enable ultrafast and potentially sub-picosecond timing. This will be done by using state-of-the-art facilities such as the laser-plasma induced 10 fs photon beams available at Berkeley Lab's BELLA Center.

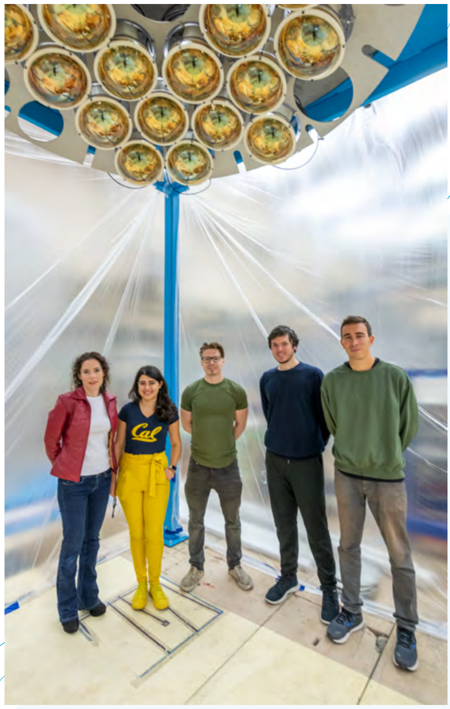
New and fast readouts of scintillation detectors can enable the in situ dose and range verification in the emerging FLASH cancer therapy and reduce the cost of positron emission tomography (PET) systems while maintaining excellent position and timing resolution.

FIVE-YEAR GOALS

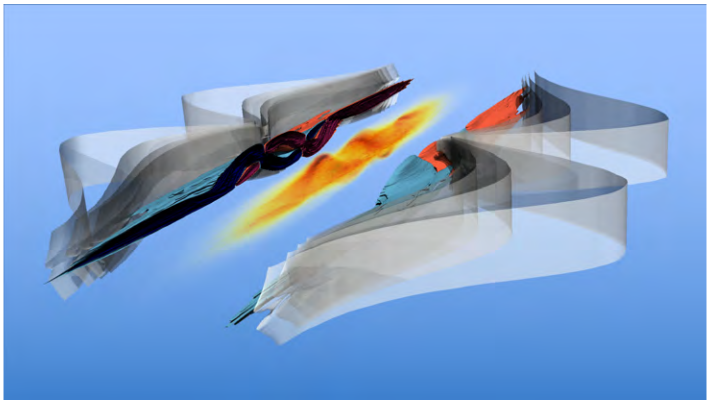
- Demonstrate fine-pitch HPGe detectors for high-resolution and high count-rate gamma-ray spectroscopy and imaging.
- Explore fundamental scintillation mechanisms to enable a first-principles approach to the design of novel scintillation detectors.

TEN-YEAR GOALS

- Develop and demonstrate novel semiconductor and scintillation detectors for medical imaging applications.
- Design, develop, and demonstrate scintillation detectors for ultrafast timing applications.



Left to right, NSD faculty scientist Gabriel Orebi Gann, UC Berkeley project scientists Zara Bagdasarian and Leon Pickard, UC Berkeley undergraduate student Joseph Koplowitz, and UC Berkeley postdoctoral researcher Tanner Kaptanoglu beneath the upper array of photomultiplier tubes of Eos. *Credit: Thor Swift/Berkeley Lab*



Computer modeling of beam-beam crossing at the interaction point of a future linear collider. *Credit: Arianna Formenti, Berkeley Lab*

ATAP mentors Jeroen van Tilborg (left) and Curtis Berger (center) talk with Johnny Chinchilla Pinto, CCI Summer 2023 Intern, about their research at the Berkeley Lab Laser Accelerator (BELLA). *Credit: Thor Swift, Berkeley Lab*

Cross section of a superconducting magnet, a vital technology for modern accelerators and many other applications. *Credit: Marilyn Sargent, Berkeley Lab*

5. ACCELERATOR TECHNOLOGY & APPLIED PHYSICS

5.1 EXECUTIVE SUMMARY AND STRATEGIC PILLARS

5.1.1 VISION

The Accelerator Technology & Applied Physics (ATAP) Division extends the frontiers of science and technology by developing particle accelerators, particle and photon sources, lasers, and magnets to explore and control matter and energy.

5.1.2 MISSION

Our mission is to advance the physics and applications of particle accelerators and related technologies that produce and control beams of ions, electrons, neutrons, and photons, creating new capabilities across the physical and life sciences. These capabilities allow researchers to explore the fundamental nature of matter and energy, support the quest for fusion energy, open new doors in cancer treatment, and drive research and applications that range from element sensing and quantum computing to national security. We lead initiatives and collaborations that advance the Department of Energy (DOE) mission through the central legacies of Berkeley Lab: particle accelerators and team science. And we develop the national scientific workforce by educating the next generation and broadening participation.

5.1.3 INTRODUCTION

Pursuing discovery science through innovation. The ATAP Division develops frontier colliders and accelerators strongly aligned with the recommendations from the 2023 report of the Particle Physics Project Prioritization Panel (P5), *Exploring the Quantum Universe: Pathways to Innovation and Discovery in Particle Physics*, as described in Section 3.1.2. These include methods for high-intensity proton beams supporting Deep Underground Neutrino Experiment (DUNE) neutrino physics and related areas at the Long-Baseline Neutrino Facility (LBNF), and for particle colliders that explore basic physics at the highest energy frontiers. A sequence of colliders is envisaged, starting with the high-luminosity upgrade of the Large Hadron Collider, now in progress, followed by the envisioned launch of an offshore Higgs factory this decade for precision physics at a fraction of a TeV, and parallel development of paths to the 10 TeV pCM (parton center-of-momentum, or parton center-of-mass) scale via proton, muon, and wakefield technologies. We develop plasma, laser, magnet, and high-energy-density science supporting fusion energy and plasma science strongly aligned with the 2020 Report of the Fusion Energy Sciences Advisory Committee, *Powering the Future*, which defines a long-range plan to deliver fusion energy and to advance plasma science. And we develop accelerators and radiation sources for broad science and applications in nuclear science, security, industry, and medicine. We do this through a combination of programs in next-generation magnets, light sources, compact plasma-based accelerators, controls and instrumentation, advanced modeling, and plasma science.

Strengthening and renewing Berkeley Lab's facilities. Accelerator science and technology support ongoing improvements to the Advanced Light Source (ALS) and the ALS Upgrade to assure the scientific vitality of this important DOE user facility and future projects as described in Section 7.4.

Contributing to national and international priorities. Recognized as a partner of choice for leading facilities, we are integral to many of today's most exciting and challenging accelerator and fusion-related projects, while developing opportunities for those of tomorrow.

A two-day Offsite Strategic Planning Retreat in Berkeley, CA, helped ATAP Division staff members and partners connect, collaborate, and build our future together. Participants worked on the division's strategic priorities for the next three to five years and their connections to scientific community and agency plans. Team-building events helped us strengthen connections, leverage creative thinking, build networks, and get to know colleagues. *Credit: Thor Swift, Berkeley Lab*

5.2 PURSUING DISCOVERY SCIENCE THROUGH INNOVATION

5.2.1 DEVELOPING NEXT-GENERATION MAGNETS

Progress in particle accelerators, and in many other fields, goes hand in hand with the achievable strength and quality of magnets, and increasingly also with their size and cost.

The Berkeley Center for Magnet Technology (BCMT), a program operated jointly by the ATAP Division and Engineering Division, offers an unparalleled set of "mesoscale to magnet" capabilities vertically integrated from the underlying materials science through magnet design, fabrication, and testing. The center leverages breadth and depth of expertise in permanent magnet and superconducting magnet technology, with long-standing expertise from the ATAP Division's Superconducting Magnet Program (SMP) and from the Engineering Division's Magnetics Engineering Department as described in Section 6.2.3.

The ATAP Division is headquarters for the multilaboratory US Magnet Development Program (US MDP), a flagship HEP effort with the mission to perform research on advanced superconducting accelerator magnet technology for future HEP colliders. The US MDP provides broad leadership in accelerator magnet technology, by (a) maintaining and strengthening US leadership in high-field accelerator magnet technology for future colliders; (b) further developing and integrating magnet research teams across the partner laboratories and US universities for maximum value and effectiveness to the program; and (c) identifying and nurturing crosscutting / synergistic activities with other programs (e.g., FES), to more rapidly advance progress towards US MDP goals. Important approaches to the longer-term vision of HEP, such as the potential Future Circular Collider or Muon Collider identified in the recent P5 report, as well as improved sensitivity in dark matter searches, will require superconducting magnets of unprecedented performance and cost-effectiveness.

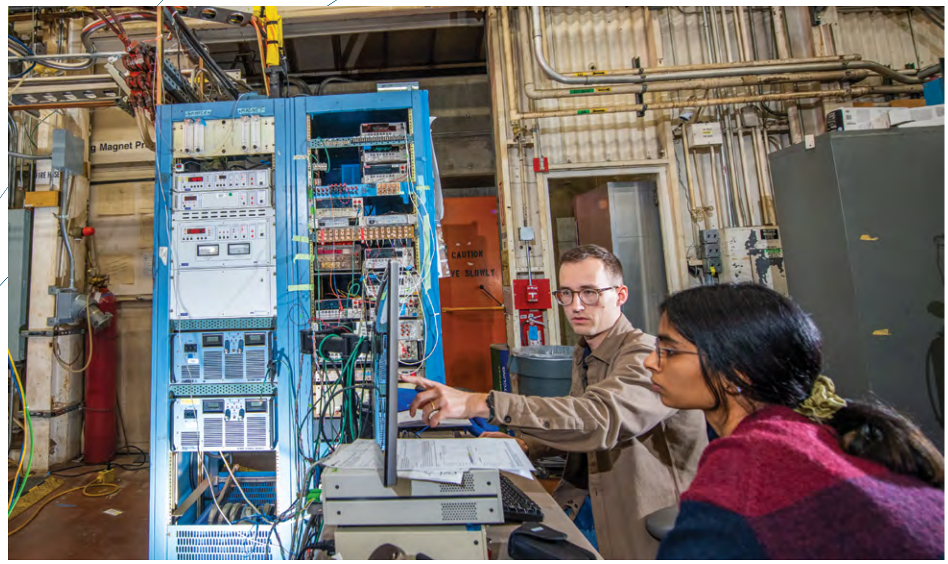
Beyond HEP, many DOE Office of Science programs and projects rely on progress in magnetics. Examples are the next generation of light sources and major accelerators, including the Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) and the Electron-Ion Collider (EIC), to be located at Brookhaven National Laboratory (BNL). These facilities critically depend on advanced superconducting magnet technology. Magnetic fusion, medical treatment accelerators, and many other fields of research and applications similarly rely on advances in magnetic systems. The BCMT has unique depth and breadth of expertise in magnet research and development (R&D) and project delivery, and is actively engaged in supporting these needs from the community.

FIVE-YEAR GOALS

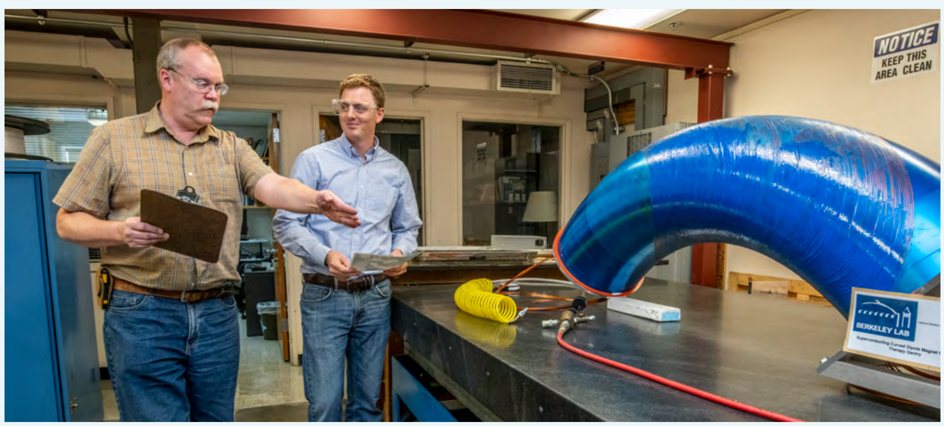
- Support completion of the High-Luminosity Large Hadron Collider (HL-LHC) Accelerator Upgrade Project in close collaboration with colleagues from Fermi National Accelerator Laboratory (Fermilab), BNL, and the National High Magnetic Field Laboratory's Applied Superconductivity Center.
- Deliver a record 15-T, large-bore dipole for the new high-temperature superconducting (HTS) cable test facility to be located at Fermilab, supporting high-field magnet development for the DOE Offices of Fusion Energy Sciences (FES) and High Energy Physics (HEP).

TEN-YEAR GOALS

- Lead and execute the US DOE Magnet Development Program Plan toward high-performance, low-cost magnets for colliders, aligned with the 2023 P5 report and future colliders.
- Support the creation of a national magnet development program for fusion, including high-temperature superconductors, through working with universities, laboratories, and industry.



Nandana Menon, a postdoctoral scholar (right), and research scientist Jean-Francois Croteau (left) analyze data for transport current measurements of Nb_3Sn wires tested at 4.2 K in a background magnetic field of up to 16-T, for superconducting magnets being built by ATAP's SMP. *Credit: Robinson Kuntz, Berkeley Lab*



Jim Swanson, an engineering technical associate, and Lucas Brouwer, a staff scientist, discuss the design of a canted cosine theta magnet (CCT) dipole magnet. The use of a superconducting magnet greatly reduces the size and weight of a beam-delivery gantry for proton and heavy-ion therapy, and the large aperture and special optics of the CCT magnet geometry accommodate a wide range of beam energies without having to change the magnetic field. *Credit: Marilyn Sargent, Berkeley Lab*

IMPROVING CANCER THERAPY WITH NEXT-GENERATION GANTRIES

Accelerated particle beams have long been used for cancer therapy that spares healthy tissues en route to the malignancy. Smaller, lighter, less expensive "treatment gantries" — the adjustable magnetic arrays that precisely guide the beam — would greatly improve hospital-based treatment facilities. Parlaying capabilities developed for high-energy physics into this application, ATAP researchers are prototyping a superconducting magnet design that has the potential to reduce the overall cost of these facilities and enable faster treatment.

5.2.2 ACCELERATOR SCIENCE AND TECHNOLOGY FOR THE NEXT GENERATION OF LIGHT SOURCES

Progress in a broad range of science and technologies, from batteries to biology, is driven by the ability to resolve new materials and processes using ever-advancing X-ray light sources and electron instruments. The next generation of science requires sources with ever-higher-brightness electron beams, as well as advanced magnetic insertion devices. We are developing technologies to realize these sources, from advanced rings like the ALS-U at Berkeley Lab (learn more about the Physical Science Area's efforts for the ALS-U in Section 7.4.), to free-electron laser (FEL) based light sources such as the Linac (linear accelerator) Coherent Light Source II High Energy (LCLS-II-HE) Upgrade Project at the SLAC National Accelerator Laboratory (originally the Stanford Linear Accelerator Center), and future sources based on plasma accelerators and electron diffraction.

Electron beam source brightness drives performance, from FELs with MHz-class repetition rates to ultrafast electron diffraction and microscopy. Building on expertise in advanced normal conducting radio frequency (RF) structures, including Continuous Wave Radio-Frequency Quadrupole (CW RFQ) accelerators for ions, allowed delivery of the LCLS-II injector at SLAC. The Advanced Photoinjector Experiment (APEX), on which it was based, has been leveraged to create HiRES, a high repetition rate beamline at the ALS where researchers are advancing ultrafast electron diffraction, testing cathodes, and developing control techniques to advance accelerator performance. The APEX-II gun adopts a two-cell cavity design and high cathode gradient to further reduce emittance and offers a normal conducting option for the LCLS-II-HE upgrade and future sources. The high accelerating gradients of laser-plasma accelerators (LPAs) are being investigated for their potential to reach ever lower emittances, for upgrades of light sources and future machines.

LPAs could create a generation of compact future light sources across a range of energies. Betatron X-rays emitted by off-axis electrons during acceleration produce broadband multi-keV X-rays with sub-micron source size enabling femtosecond high-resolution phase-contrast imaging and X-ray transmission spectroscopy. Colliding monoenergetic LPA beams with a scatter laser (known as Compton scattering) produces tunable monoenergetic MeV gamma rays with the potential to increase sensitivity and reduce dose across a range of nuclear, medical, and imaging applications. Compact FELs to enable a broad range of applications are being pursued by combining high beam quality LPAs with precise beam transport and phase-space manipulation optics, followed by well-tailored undulator configurations.

Ultrafast electron diffraction (UED), by providing significant complements to X-ray-based instruments, has enabled groundbreaking studies in condensed matter physics, chemical science, and biology. The HiRES beamline offers unique opportunities to push the technology to higher spatial and temporal resolution.

FIVE-YEAR GOALS

- Demonstrate plasma-accelerated free-electron lasing and other X-ray sources.
- Develop ultrafast and time-resolved electron nanodiffraction techniques.
- Test cathode materials and techniques to advance injector and free-electron laser (FEL) performance.

TEN-YEAR GOALS

- Develop a new generation of high-brightness electron sources, FELs, and X-ray sources.
- Simulate ultralow-emittance beams and storage ring lattices from end to end.
- Model accelerator and photon production systems from start to end.
- Develop multimodal ultrafast electron scattering instrumentation.

FIVE-YEAR GOALS

- Produce 10 GeV electron beams from a single LPA module.
- Stage two LPA modules with high efficiency at multi-GeV energies.
- Create low energy spread multi-MeV photons via laser backscatter from an LPA.
- Produce muons at 10 GeV and above.
- Develop high-average and high-peak power coherently combined fiber laser systems.

TEN-YEAR GOALS

- Develop high beam quality from single and staged LPAs.
- Develop end-to-end design concept for LPA-based linear colliders at 10 TeV energies.
- Produce coherent soft X-rays from an LPA-based FEL.
- Initiate staging of ion acceleration beyond 100 MeV.
- Construct and operate a kHz facility (kBELLA) driven by a multi-kW laser system.

5.2.3 ULTRA-COMPACT ACCELERATORS AND RADIATION SOURCES FOR SCIENCE, SECURITY, AND MEDICAL APPLICATIONS: BELLA AND KBELLA

LPAs are a promising candidate for the next generation of compact, less expensive particle accelerators because they can produce electric field gradients more than 100 times higher than conventional accelerators. LPAs use an intense laser pulse to drive a large amplitude wave in a plasma. The electric field of this wave rapidly accelerates particles to high energies.

The Berkeley Lab Laser Accelerator (BELLA) Center is the world-leading program in the development of laser-plasma electron accelerators and related experiments. It includes state-of-the-art petawatt and hundred terawatt lasers with multiple beamlines enabling unique experiments on staging of modules, light sources and advanced laser technologies, and broad collaborative and user experiments.

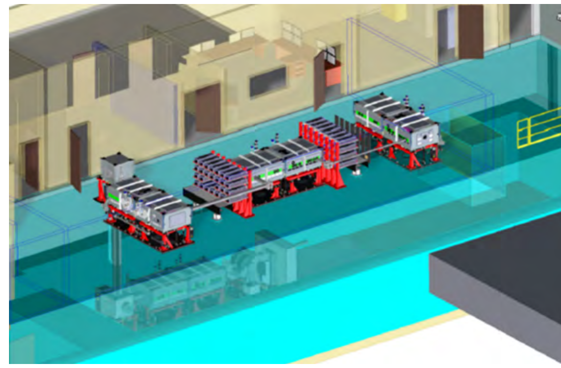
From left, research scientists Marlene Turner and Alexander Picksley and staff scientist Anthony Gonsalves align the BELLA petawatt second beamline, which allows two synchronized laser pulses on target for applications, such as the coupling of multiple LPA stages to extend the energy reach of these compact accelerators towards future colliders.
Credit: Marilyn Sargent, Berkeley Lab

Research on LPAs addresses a national need to develop compact, high-field accelerators and high-power lasers. Along the path toward a future 10 TeV particle collider to expand understanding of fundamental physics, as highlighted in the 2023 P5 report, LPA and laser development will benefit many applications and fields, including the following:

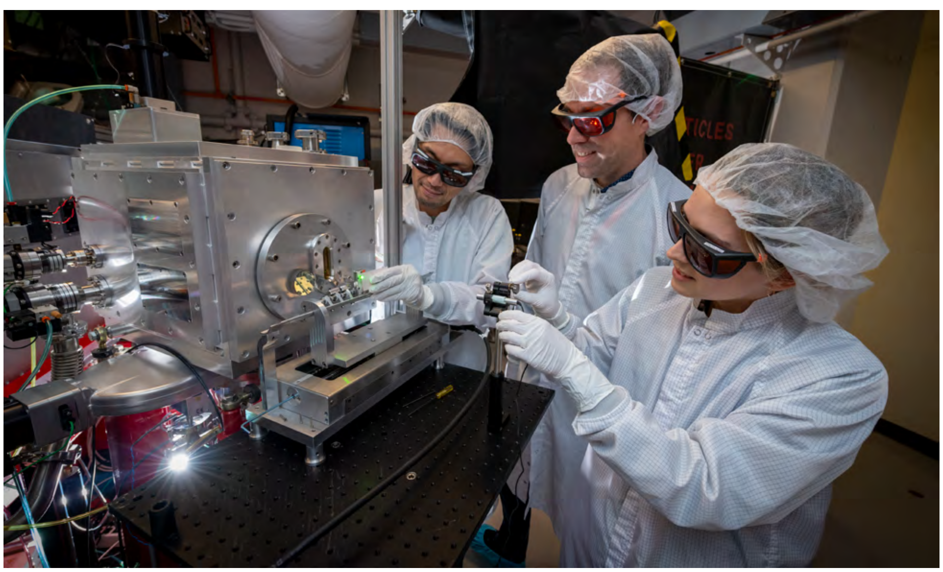
- Laser ion accelerators for biophysics research, including FLASH therapy, and potentially a next generation of radiotherapy medical devices.
- Compact FELs for ultrafast science.

- Monoenergetic sources of MeV photons for nonproliferation and for nondestructive testing.
- High-energy muon and ion sources.
- Techniques for creating and probing high-energy-density matter and unique material states for inertial fusion and quantum information science (QIS).
- Tests of high-field quantum electrodynamics.
- Many other examples of "bringing the accelerator to the application" in research and industry.

To drive the next generation of laser accelerator applications, including future LPA-based colliders, novel laser technology must be developed to deliver high-average and high-peak power, in ultra-short pulses. Fiber laser technology is being developed to generate such intense laser pulses at multi-kHz repetition rates in highly efficient, compact, robust monolithic architectures through the coherent combining of many fiber pulses in both space and time. A future laser facility is planned, kBELLA, that will operate at kHz repetition rates and kW average powers to enable higher performance LPA via active feedback and user experiments and applications.



Computer-aided design (CAD) rendering of the proposed kBELLA facility, which will include precision LPAs driven by a high-average power laser system. This user facility will be a crucial step towards a future 10 TeV collider and will secure US leadership in advanced particle accelerators and enable applications in physics, materials, security, and biomedical science. *Credit: Zachary Eisentraut, Berkeley Lab*



Left to right, Kei Nakamura, a staff scientist in the ATAP Division, Antoine Snijders, a former senior scientist in the Biological Systems and Engineering Division, and Lieselotte Obst-Huebl, a research scientist in the ATAP Division, at the BELLA Center adjusting a cartridge containing cancer cells at the end of the BELLA PW Proton beam line for FLASH radiobiology studies. *Credit: Thor Swift, Berkeley Lab*

FIVE-YEAR GOALS

- Advance adaptive fast feedback control with artificial intelligence (AI) and machine learning (ML), enabling enhanced accelerator performance and high-power fiber lasers.
- Scale up qubit control for superconducting quantum processors.
- Develop next-generation normal conducting RF cavities with improved gradient and efficiency.

TEN-YEAR GOALS

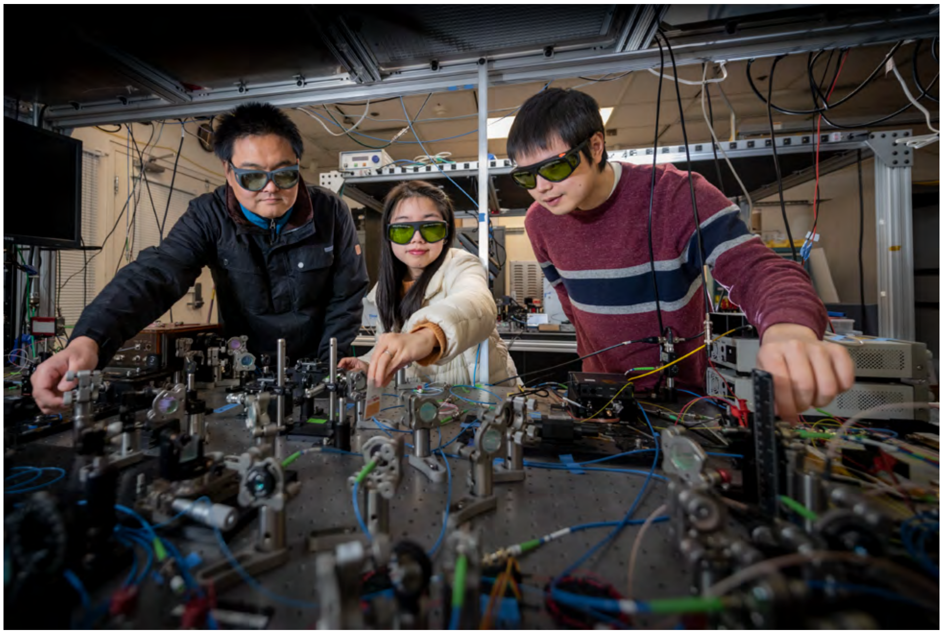
- Pioneer transformative low-level radio frequency (LLRF) controls for performance, accuracy, and stability.
- Lead RF cavity R&D for future accelerators, including a 10 TeV pCM muon collider.
- Develop and implement AI/ML for accelerator performance.

5.2.4 ACCELERATOR CONTROLS AND INSTRUMENTATION AND NOVEL LASER TECHNOLOGY

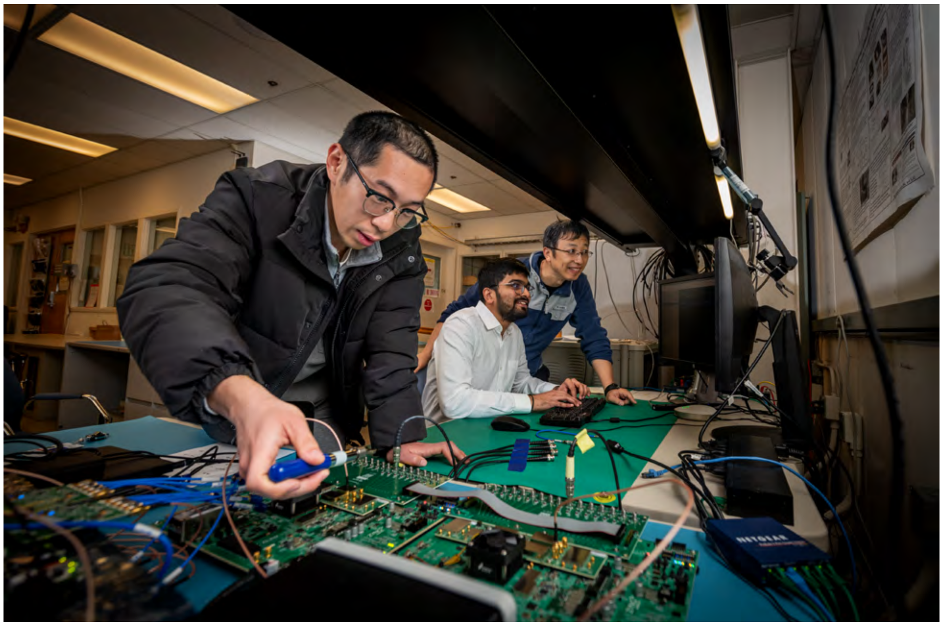
The next frontiers in accelerators, colliders, lasers, quantum systems, and other applications all require unprecedented precision in controls and instrumentation. The Berkeley Accelerator Controls and Instrumentation (BACI) Program—in collaboration with the Engineering Division and other divisions—drives performance in classical and reinforced ML control and feedback, as well as in RF systems and cavities for accelerators.

RF systems are critical to the cost-capability curve of accelerators. We are improving acceleration gradient and efficiency through innovative topologies and geometries, and advanced materials and manufacturing. These are vital to future accelerators and colliders, such as muon colliders.

To meet ever-increasing requirements for high-quality RF structures and sophisticated control requirements in modern accelerators and colliders, we advance the state of the art in LLRF controls based on field-programmable gate arrays (FPGAs). This also creates controls advancing quantum computing and



From left to right, Qiang Du, a staff scientist in the Engineering Division, Dan Wang, a research scientist in the ATAP Division's BACI Program, and Tong Zhou, a staff scientist in the ATAP Division's BELLA Center, tune a coherently combined fiber laser in a multiprogram lab.
Credit: Thor Swift, Berkeley Lab



From left to right, Yilun Xu, a research scientist, Neel Rajeshbhai Vora, a scientific engineering associate, and Gang Huang, a staff scientist, test QubiC 2, an open-source FPGA-based control system for superconducting quantum computing. *Credit: Thor Swift, Berkeley Lab*

plasma accelerator performance. And we are using these controls to enable a new generation of high-energy, short-pulse fiber lasers with unprecedented peak and average power capabilities that we are developing.

We aim to develop machine learning-based methods to enhance the performance of particle accelerators. The HiRES beamline is a vital testbed to characterize RF cavities and photocathode materials, develop critical beam diagnostics, control, and timing synchronization instrumentation, and test various AI/ML algorithms.

FIVE-YEAR GOALS

- Lead DOE SciDAC (Scientific Discovery through Advanced Computing Program) projects, including the Collaboration for Advanced Modeling of Particle Accelerators (CAMPA) for HEP, and Kinetic IFE (Inertial Fusion Energy) Simulations at Multiscale with Exascale Technology (KISMET) for FES.
- Support US accelerators (e.g., BELLA complex, FACET-II, Fermilab Complex), light sources, fusion R&D, and LaserNetUS as part of SimNetUS.
- Develop collider designs towards 10 TeV pCM based on proton, muon, or wakefield technologies and develop future light sources.
- Support the US DOE inertial fusion energy program and EIC.

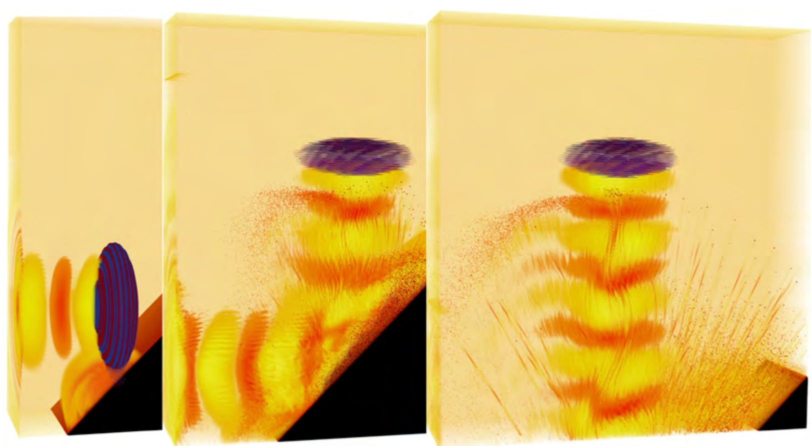
TEN-YEAR GOALS

- Maintain leadership in the modeling of beams, particle accelerators, plasmas, and fusion at the multi-exascale performance level.
- Develop cutting-edge algorithms and models including AI/ML and/or quantum computing.
- Carry out virtual realizations of particle accelerator “twins” and superfacilities for beam physics, design, and concept development.

5.2.5 ADVANCED COMPUTER MODELING

Computer modeling is essential to the study—and successful operation—of beams, particle accelerators, plasmas, and fusion devices, and the complexity of the simulation software is now routinely commensurate with the experiment simulated. The ATAP Division’s Advanced Modeling Program (AMP) draws on deep collaboration among physicists, applied mathematicians, and computer scientists to develop cutting-edge computing techniques and codes for fast and accurate simulations of particle beams and accelerators, plasma and fusion devices, and more.

The AMP leads trans-institutional efforts, such as DOE’s Exascale Computing Project, including the Collaboration for Advanced Modeling of Particle Accelerators (CAMPA) and the Kinetic IFE (Inertial Fusion Energy) Simulations at Multiscale with Exascale Technology (KISMET) collaborations. We manage the Beam, PLasma & Accelerator Simulation Toolkit (BLAST) Program, the backbone of a coherent ecosystem of advanced open-source codes, including the 2022 Gordon Bell Prize winner WarpX. The AMP’s researchers are leveraging these efforts to prepare the next generation of projects, such as a Higgs factory, a 10 TeV pCM collider based on proton, muon, or wakefield technologies, the EIC, improvements to the Fermilab complex, and next-generation light source and fusion power plant concepts.



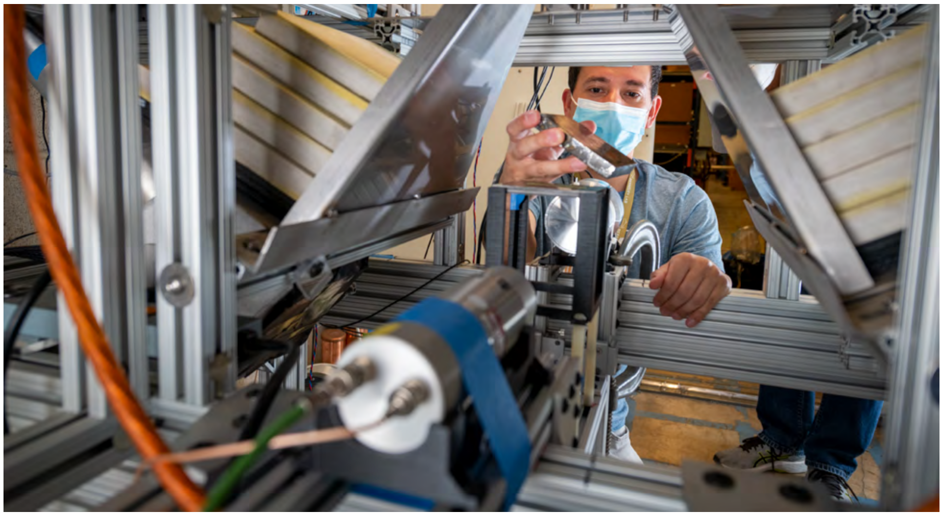
Computer-generated images using AMP’s exascale code, WarpX, which enables the computational study and design of novel concepts for the generation and acceleration of bright, high-charge electron beams across accelerator categories. In this novel hybrid solid-gas target concept, a laser (red and blue) generates high-amplitude electric fields (solid yellow and orange) by ionization of an ambient gas (light yellow), which are used to trap and accelerate a high-charge electron beam (particles trapped behind the laser) that is extracted during the reflection of the laser on a solid-density plasma mirror (black and brown). These beams could be used for various applications, including treating some types of cancers using FLASH radiotherapy. *Credit: Axel Huebl, Berkeley Lab*

5.2.6 PLASMA SCIENCE FOR ACCELERATORS AND APPLICATIONS

Particle beam and plasma technologies create capabilities for a range of fields including fusion energy sciences, planetary and earth science, and QIS. To realize these, the Fusion Science and Ion Beam Technology (FS&IBT) Program develops novel accelerator, sensing, and quantum methods.

We develop and use novel plasma sources, particle sources, and particle accelerators for basic and applied science and often transfer them to applications at other labs or in industry. New directions include forming more compact, lower-cost ion accelerators, controlling plasmas for energy applications, and generating neutrons for novel imaging applications.

We are developing neutron-based imaging techniques, where precise tracking of neutrons enables the 3D imaging of materials and their elemental distribution. These methods are being developed for imaging carbon distributions in soil (an important indicator of soil health) and for a wide range of applications that include energy science, national security, nuclear data, and space science.



Mauricio Ayllon Unzueta, a research scientist in the ATAP Division, loads a sample from a meteorite into an elemental mapping instrument at Berkeley Lab, which uses neutron scattering to probe samples. *Credit: Thor Swift, Berkeley Lab*

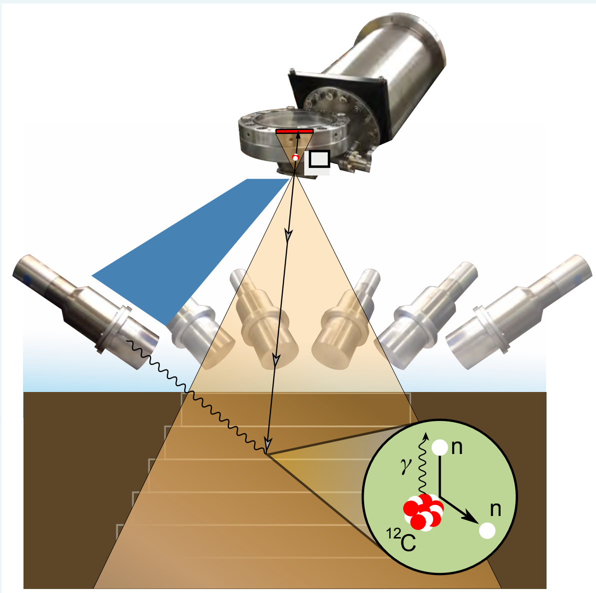
FIVE-YEAR GOALS

- Develop low-cost, compact ion linacs and applications from ion implantation to radiation effects testing of materials.
- Develop neutron-scattering techniques for nondestructive elemental analysis of materials.
- Explore spin-photon qubit synthesis with beams and plasmas; optimize and integrate selected emitters.

TEN-YEAR GOALS

- Develop beam and plasma applications in fusion energy sciences, manufacturing, and national security.
- Advance neutron-scattering techniques for high-precision materials characterization and develop robust, fast, and compact systems.
- Develop reliable processes for qubit synthesis and integrate increasing numbers of highly coherent quantum emitters for quantum networking and quantum sensing.

QIS is rapidly emerging, and the race is on to discover, optimize, and integrate increasing numbers of highly coherent qubits for specific applications. ATAP's FS&IBT Program is driving discovery and synthesis of spin-photon qubits with beams and plasmas for applications from quantum sensing to quantum networking.



Artist's rendering of non-destructive imaging with neutrons, which provides a faster and more detailed image of the amount and distribution of elements in a target material without disturbing the sample, supporting soil analysis as well as mining and planetary exploration. *Credit: Arun Persaud and Susan Brand, Berkeley Lab*

IMPROVING ELEMENTAL 3D MEASUREMENTS

Recent ATAP Division research to improve Associated Particle Imaging (API) could allow this nuclear imaging technique to expand into applications that require nondestructive elemental analysis, including measuring the soil carbon content of acre-sized agricultural fields at depths of 30 centimeters in collaboration with Berkeley Lab's Earth and Environmental Sciences Area (EESA) and Adelphi Technology, as well as for planetary science missions, including sample return missions and prospecting and mining on Mars or the Moon, and for security applications. Such sources are supported by the US DOE Office of Fossil Energy and Carbon Management and Office of Technology Transitions, and by NASA.

Boubacar Kanté (second from left), a professor at the University of California, Berkeley, and a faculty scientist in Berkeley Lab's Materials Sciences Division, Thomas Schenkel, a senior scientist in the ATAP Division (with a marker in hand), and co-researchers work on the silicon-based quantum light project. *Credit: Thor Swift, Berkeley Lab*

5.3 ADVANCING NATIONAL AND INTERNATIONAL PRIORITIES

The next generation of colliders, light sources, and fusion devices will be multi-institutional and international. Multi-program research across accelerators, colliders, fusion, and applied physics, combined with decades of collaboration, make the ATAP Division an important partner in realizing such large-scale projects across the DOE complex and beyond.

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

The world's largest particle collider, the LHC, discovered the Higgs boson. Upgrades aim to increase its luminosity by an order of magnitude. 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.

A critical part of the accelerator upgrade is higher-strength magnets to focus the particle beams more tightly (the interaction region quadrupoles) using advanced niobium-tin superconductors. Berkeley Lab has been a key contributor throughout, with primary responsibility for cabling and magnet assembly, working closely with partners Fermilab and BNL. The project comes out of years of leadership in superconducting magnet technology, from basic to directed research to projects. The US delivered the first cryoassembly in the fall of 2023, and hardware installation into the tunnel is slated to begin in 2026.

5.3.2 LINAC COHERENT LIGHT SOURCE II HIGH ENERGY (LCLS-II-HE) UPGRADE AND FREE-ELECTRON LASER PROJECTS

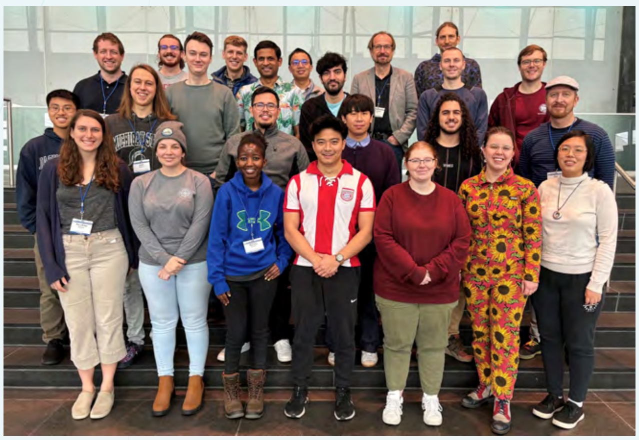
The Linac Coherent Light Source II High Energy (LCLS-II-HE) Upgrade Project is currently underway at SLAC. For this project, the superconducting accelerator energy will be doubled from 4 GeV to 8 GeV. To maintain the desired soft X-ray spectral range, new magnetic components for the soft X-ray undulators, with a longer wavelength for the magnetic undulations, are required. As a partner lab for the project, Berkeley Lab is responsible for the design and manufacturing of new magnetic undulator components. Berkeley Lab also made modifications to the existing undulator mechanical system to accommodate the higher magnetic force of the new magnetic components. Berkeley Lab is responsible for delivering nine new soft X-ray undulators as well as the components to update 21 existing soft X-ray LCLS-II undulators at SLAC. Berkeley Lab is contributing to the LCLS-II-HE Upgrade Project in beam-dynamics modeling and LLRF control systems and developing technology for this and future FELs.

FIVE-YEAR GOALS

- Support the delivery of the high-field quadrupole magnets for the HL-LHC Accelerator Upgrade Project at CERN (the European Organization for Nuclear Research).
- Provide critical accelerator technologies for the success of LCLS-II-HE.
- Contribute to formation of a public fusion magnet program with synergies to HEP's Magnet Development Program and public-private partnerships.

TEN-YEAR GOALS

- Support an international Higgs factory and other critical accelerator projects.
- Construct and operate a kHz laser facility (kBELLA) driven by a multi-kW laser system.
- Support the EIC through expertise including beam-beam simulations, controls, and superconducting magnets.
- Translate R&D developments in accelerator technologies into capabilities for new projects that extend physics reach.
- Advance high-energy-density science and applications to inertial fusion, material testing, and plasma heating for future fusion reactors.
- Develop the accelerator and fusion workforce, leveraging R&D in beams, plasmas, magnets, modeling, instrumentation, and QIS.



Christoph Steier, a senior scientist at the ALS Upgrade Project, and Thorsten Hellert, an ATAP research scientist (back row, far right), were among the instructors for the January 2024 US Particle Accelerator School course in beam-based diagnostics.
Credit: US Particle Accelerator School

Paolo Ferracin, a senior scientist from the ATAP Division, teaches a class on superconducting magnets for particle accelerators at a recent Joint Universities Accelerator School (JUAS) session.
Credit: JUAS

USPAS, JUAS, CERN ACCELERATOR SCHOOL – HIGHER EDUCATION FOR THE ACCELERATOR COMMUNITY

Particle accelerator science and technology is seldom available through traditional collegiate programs, making specialty schools offering expertly taught courses vital resources to develop the future of the field. Berkeley Lab personnel, especially from the ATAP Division as well as the Engineering Division and Nuclear Science Division (NSD), have taught extensively at the US Particle Accelerator School (USPAS) since its early days.

More than 80 people associated with ATAP have taught at USPAS in a total of more than 100 courses. Many of these courses are team taught with colleagues from other institutions, building lasting connections throughout the accelerator community. ATAP personnel also teach at the CERN Accelerator School and the Joint Universities Accelerator School (JUAS), and offer short courses in association with the major technical conferences.

5.3.3 FUSION ENERGY SCIENCE

With demonstration of ignition in laser-driven inertial confinement fusion, and record energy and temperature in magnetic confinement fusion, interest in fusion energy is strong, and private investment is increasing. Berkeley Lab develops advanced beams, plasmas, magnets, and instrumentation. These technologies support FES, future projects, and the quest for fusion power across approaches, from magnetic to inertial confinement.

THE PATH FORWARD TO FUSION ENERGY

Fusion energy is one of the biggest challenges of our time, and the same process that powers our sun could provide a near-limitless supply of safe and carbon-free energy that could also address high energy prices and pollution. ATAP Division researchers are trying to make the path forward to fusion energy a reality, and they have produced niobium-tin cables to create more powerful superconducting magnets, new high-temperature superconductor methods, and new types of lasers that could extend the capabilities of particle accelerators and realize the promise of fusion.

Reed Teyber, Research Scientist, prepares for testing of high-temperature superconducting cables in a liquid nitrogen bath. This research supports conductor characterization and testing of novel cable and magnet diagnostics and instrumentation for fusion energy applications. *Credit: Thor Swift, Berkeley Lab*

Research is underway to develop magnet technology using commercially available rare earth barium copper oxide (REBCO) high-temperature superconductors and associated cable architectures for fusion, and the instrumentation, diagnostics, and magnet protection paradigms to enable the reliable and rapid implementation of these advanced superconductors. Expertise in modeling and analysis, diagnostics, materials characterization, magnet fabrication, and magnet testing supports FES and the nascent fusion industry.

Simulating the complex interactions of charged particles, fields, and structures from first principles, enabled by exascale codes like WarpX, allows the modeling of complex plasma and fusion devices. This helps us to understand kinetic effects in laser-driven IFE and laser-driven ion beam generation and acceleration. WarpX is also being used to simulate alternative fusion designs for several private companies.

Exploring fundamental plasma processes at high precision and repetition rates in flexible experimental setups is critical to fusion. Mid-scale facilities like BELLA as part of LaserNetUS develop compact particle and radiation sources, diagnostics, target engagement, and AI/ML methods for IFE, high-energy-density physics (HEDP), and QIS applications. Applications include sources suitable for high-precision probing of dense plasmas to improve our understanding of inertial fusion physics, for fast ignition drivers in inertial confinement fusion, and for creating new materials for QIS and superconductivity.

Hailang Pan (left), SULI student, adjusting an ultrafast laser at the BELLA Center with mentor Tong Zhou, Staff Scientist in ATAP Division. *Credit: Thor Swift, Berkeley Lab.*

5.3.4 FUTURE COLLIDERS AND NEUTRINO EXPERIMENTS

The 2023 P5 report lays out a bold vision for future particle colliders, beginning with an offshore Higgs factory and continuing through a collider at the 10 TeV pCM scale. The ATAP Division is engaged with Higgs factory efforts and working actively to deliver feasible and well-defined technologies and plans for project evaluation. These include developing advanced simulations, magnet designs, and RF. We are a leader in technologies critical to proton, muon, and wakefield paths to 10 TeV ranging from high-strength magnets, to RF cavities in magnetic fields, to LPAs and large-scale precision simulations. We are also supporting the advancement of the Fermilab accelerator complex through simulation, controls, RF, and other technologies. We engage with national and international collaborations and coordinate closely with the Physics Division to realize these challenging technologies and to enable machines that can extend the boundaries of our physics understanding.

5.3.5 PRECISION LASER-PLASMA ACCELERATOR FACILITY (KBELLA)

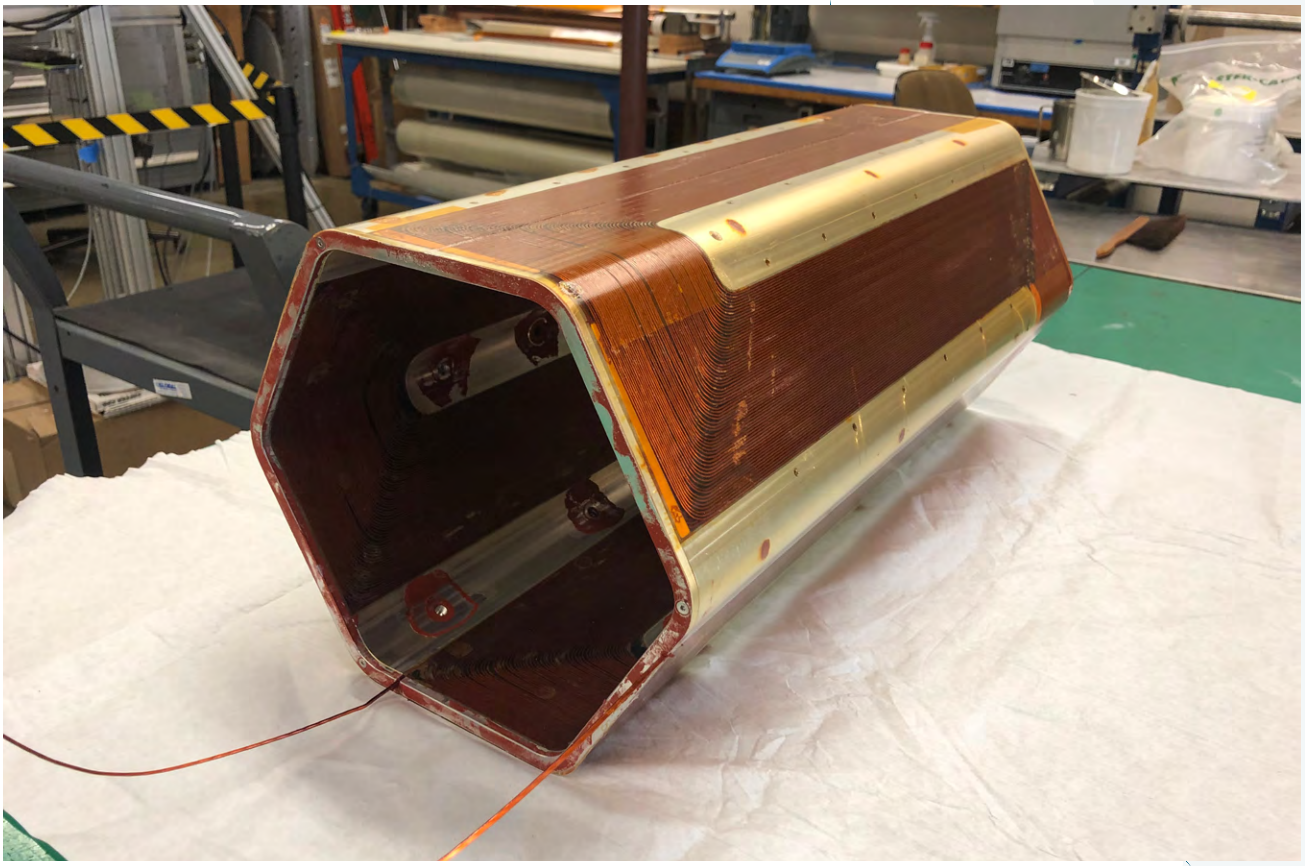
To enable the next generation of LPA R&D, highlighted in the 2023 P5 report as a path towards a future 10 TeV pCM collider, and also nearer-term applications, the ATAP Division has proposed the kBELLA facility. The laser at the heart of kBELLA is based on new technology that generates ultra-short laser pulses at the very high peak powers required to drive LPAs and related science at a much higher pulse repetition rate than current systems. By generating pulses at rates above 1 kHz (a thousand pulses per second) instead of the 1 Hz currently possible, this laser will allow active feedback control to enable the LPA to operate at unprecedentedly high stability and high beam quality. This high repetition rate is also needed to drive future colliders and a variety of real-world applications using the particle and photon beams produced. Fiber laser technology is being developed to generate intense laser pulses at the kHz repetition rates required by kBELLA. Fiber lasers can provide highly efficient, compact, robust monolithic laser architectures, and high pulse energy can be obtained by the coherent combining of many fiber pulses in both space and time. The kBELLA facility will be available for user experiments and research on a wide variety of applications. These include unique ultrafast science enabled by simultaneous delivery of laser pulses, electron bunches, and short bursts of X-rays.

5.3.6 ELECTRON-ION COLLIDER

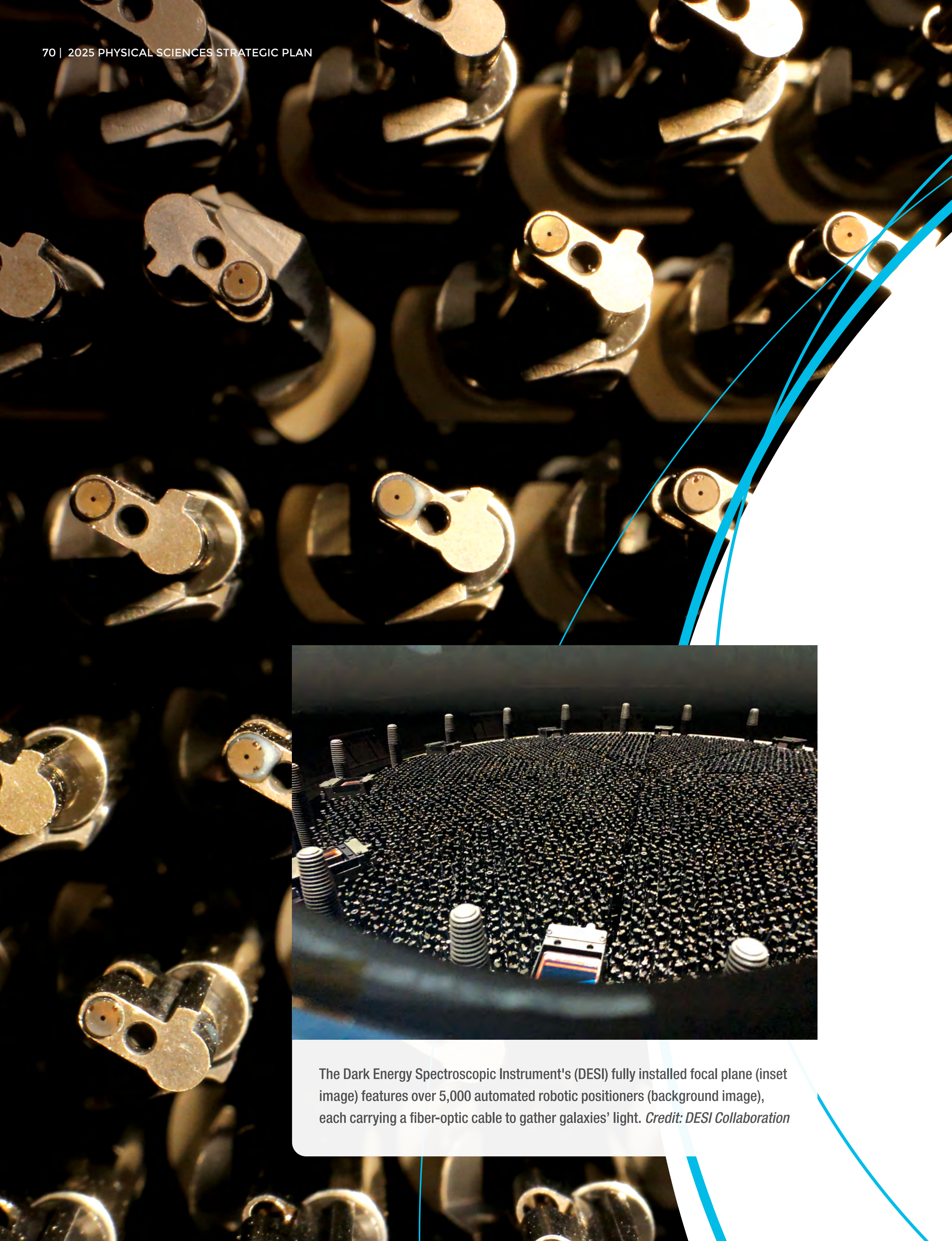
Berkeley Lab is committed to supporting the EIC project with a breadth of expertise. We are actively engaged in modeling critical accelerator physics aspects, including beam-beam simulations. Magnet technologies we develop are being applied to deliver large-aperture quadrupoles critical to the interaction region. LLRF and controls capabilities are ready to contribute to the machine's aggressive performance requirements.

5.3.7 FACILITY FOR RARE ISOTOPE BEAMS AND ELECTRON CYCLOTRON RESONANCE MAGNETS

The BCMT's expertise supports state-of-the-art electron cyclotron resonance (ECR) magnets for FRIB. In 2023, a complete ECR magnet system was commissioned and put into operation. Work on the next generation of high-field ECR ion sources using Nb_3Sn superconductors is underway. This technology will provide an increased temperature margin, enabling more aggressive operational parameters and ultimately higher cyclotron frequency. In parallel, we are working with the 88-Inch Cyclotron to develop a new ECR magnet system architecture, Mixed Axial and Radial Field System (MARS), that promises higher frequency operation while still using the established NbTi superconductor.



MARS magnet practice winding demonstrating capabilities for ECR sources for accelerators, developed through a collaboration led by Dan Xie, a staff scientist at the 88-Inch Cyclotron, and Paolo Ferracin, a senior scientist at the BCMT. *Credit: Paolo Ferracin, Berkeley Lab*



The Dark Energy Spectroscopic Instrument's (DESI) fully installed focal plane (inset image) features over 5,000 automated robotic positioners (background image), each carrying a fiber-optic cable to gather galaxies' light. *Credit: DESI Collaboration*

6. ENGINEERING

6.1 ADVANCING SCIENCE BY DESIGN

Berkeley Lab scientists, engineers, and technical staff work closely together to conceive, design, and build the unique instrumentation necessary for world-class scientific research. The remarkable results of this successful collaboration are mentioned throughout this document and are the basis of Berkeley Lab's outstanding scientific research and engineering record. As Berkeley Lab grew and its programs became more diverse, it became advantageous to centralize the delivery of engineering capabilities and expertise, and the Engineering Division was formed. In this way engineering disciplines are supported through expert groups, and a Lab-wide engineering standard is maintained in LBNL's programs and projects.

The division maintains core capabilities and deep subject matter expertise to support multiple programs across Berkeley Lab. While embedded within the Physical Science Area, the Engineering Division also supports major projects and programs in the other Berkeley Lab areas. Well-trained engineering and technical staff are deployed as needed in a matrix model to operate and maintain large facilities including the Advanced Light Source (ALS), the 88-Inch Cyclotron, and the Berkeley Lab Laser Accelerator (BELLA) Center, and to construct complex instrumentation projects like the ALS Upgrade (ALS-U), the Cosmic Microwave Background Stage 4 (CMB-S4) Project, the Deep Underground Neutrino Experiment (DUNE), A Toroidal LHC Apparatus (ATLAS), the Muon-to-Electron Conversion Experiment (Mu2E), the Electron-Ion Collider (EIC), and the Gamma-Ray Energy Tracking Array (GRETA). The staff also provide technical and engineering expertise to the science programs at Berkeley Lab.

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

Technical groups within the Engineering Division 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 DOE's and other sponsors' investments.

FIVE-YEAR GOALS

- Provide the engineering skills and technological capabilities needed for the science projects and programs at Berkeley Lab.
- Advance the requirements for a new engineering central building to replace building 46.
- Establish a funding source for continued technology R&D by Engineering Division staff.
- Strengthen Systems Engineering expertise in the Engineering Division to support small and large projects.
- Foster the ongoing development of a workplace culture centered on continuous learning and professional growth within the Engineering Division.
- Strengthen media and web presence and communications tools within the Engineering Division and to the public to promote understanding and support for the importance of engineering in scientific advancements.

TEN-YEAR GOALS

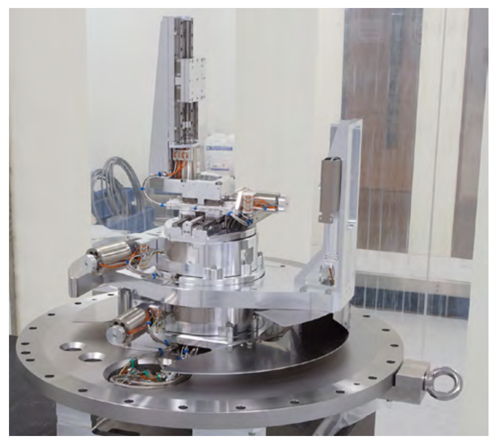
- Support Berkeley Lab's mission in partnering with the science divisions on projects and programs.
- Provide and explore cutting-edge manufacturing capabilities in areas where US industry does not have capabilities and/or capacity.
- Develop technology and engineering practices and educate the next generation of engineers.
- Provide unique engineering and fabrication engineering solutions to address the nation's grand scientific challenges.

6.2 ENGINEERING DISCIPLINARY AREAS

6.2.1 MECHANICAL ENGINEERING DEPARTMENT

The Mechanical Engineering Department is organized into engineering discipline groups, a manufacturing group, and a technologists group. The department includes core areas of expertise such as accelerator instrumentation, X-ray optics instrumentation, precision (nanoscale) engineering, and large detector systems design. The Mechanical Engineering Department manages projects throughout their entire lifecycle from project planning to conceptual development through requirements management, design, manufacturing, technical assembly, commissioning, and operation.

Reflectometer for characterizing mask blanks for the semiconductor industry. *Credit: Seno Rekawa, Arnaud Allezy, Dima Zaytsev, and the Center for X-Ray Optics.*



Physicists and engineers at Berkeley Lab are constructing GRETA, a highly sensitive gamma-ray detector, to be installed at the Facility for Rare Isotope Beams (FRIB). When assembled, the blue metal structures will hold the aluminum sphere in place, and the sphere's large, round holes will be filled with crystalline detectors. *Credit: Marilyn Sargent, Berkeley Lab*

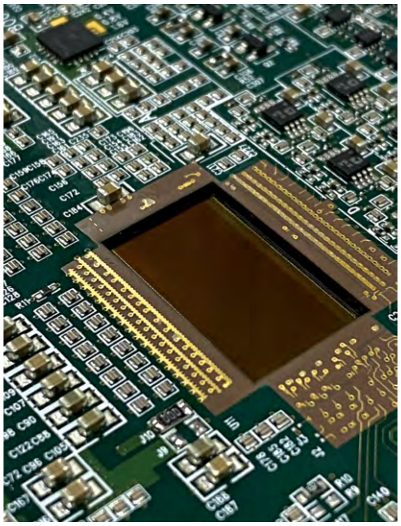
FIVE-YEAR GOALS

- Enhance optomechanical and ultrahigh vacuum skills for the next generation of beamlines and endstations, wavefront-preserving X-ray optics, and EUV (extreme ultraviolet) lithography beyond high numerical aperture.
- Build out the infrastructure and resources needed to support the engineering and testing of detector elements operating at sub-Kelvin temperatures.
- Establish programs to attract and retain top-tier talent, including training opportunities, and professional development initiatives for staff and researchers.

TEN-YEAR GOALS

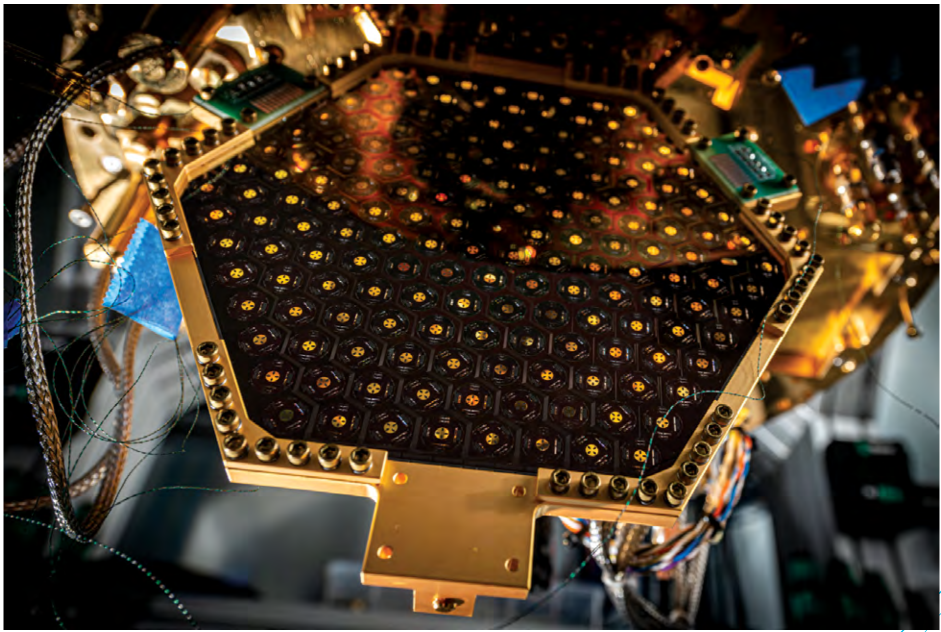
- Develop precision instrumentation enabling beyond-state-of-the-art x-ray optical coatings and nano-diffractive optics.
- Develop composites, matrix resins, and adhesives for harsh and radiation environments.
- Advance the division's technical measurement capabilities, such as multilateration techniques for alignment of scientific equipment.
- Upgrade machining capability for manufacturing large parts and maintain capabilities not of interest to industry but essential to our projects.
- Strengthen partnerships with industry leaders and academic institutions to leverage external expertise, funding, and collaborative opportunities in mechanical engineering research.

6.2.2 ELECTRONICS, SOFTWARE, AND INSTRUMENTATION DEPARTMENT



The Electronics, Software and Instrumentation Engineering (ESIE) Department comprises engineering groups in addition to a technologists' group. Core expertise areas for ESIE are radio-frequency and high-voltage engineering, data acquisition, high- and low-level control systems, semiconductor detectors, integrated circuit design and data processing, electronics system design, operations for detector systems and accelerator technology, and safety and interlock systems.

The QERLIN sensor, a 7.5 Megapixel back illuminated complementary metal-oxide-semiconductor (CMOS) imager with 5 micron pixels and high quantum efficiency in the 200–1,000 eV X-ray energy range for the QERLIN 2D RIXS spectrometer at the Advanced Light Source. The sensor (in the center, and shown before wirebonding) is operated at -50C and is thermally isolated from the in-vacuum readout electronics. *Credit: Azriel Goldschmidt, Berkeley Lab*



The CMB-S4 Prototype Detector Array installed in the dilution refrigerator for cryogenic temperature characterization. *Credit: Thor Swift, Berkeley Lab*

FIVE-YEAR GOALS

- Expand state-of-the-art hybrid Monolithic Active Pixel Sensors (MAPS) for emerging particle detection applications such as the EIC and next-generation colliders.
- Strengthen electrical engineering expertise in the department to support large-scale projects and programs.
- Apply embedded field-programmable gate array (FPGA) technology to reconfigurable online processing and AI/ML.
- Develop low-power silicon photomultiplier (SiPM) readout ASICs to enable new capabilities in mobile neutron detection, next-generation dark matter detectors, and emerging liquid-based light detectors.

TEN-YEAR GOALS

- Design and deliver state-of-the-art instrumentation for emerging detector systems worldwide.
- Migrate legacy analog low-level radio frequency (LLRF) accelerator control systems to new FPGA or radio-frequency system-on-chip (RFSOC) based high-stability systems.
- Establish beamline controls based on the Experimental Physics and Industrial Control System (EPICS) to improve data throughput, performance, and maintainability.
- Make solid-state high-power amplifiers the technology of choice for accelerator RF systems.
- Advance the state-of-the-art in deep cryogenic electronics (both silicon- and superconductor-based).
- Acquire competency in emerging technologies such as silicon photonics to serve Berkeley Lab's mission.

FIVE-YEAR GOALS

- Deliver the high-field magnets for the HL-LHC Accelerator Upgrade Project.
- Deliver accumulator ring, transfer lines, and storage ring accelerator magnets for ALS-U.
- Complete the LCLS-II/LCLS-HE undulators for the SLAC National Accelerator Laboratory.
- Build and deliver a 15T large-bore dipole for the new high-temperature superconducting (HTS) cable test facility, to be located at Fermilab.
- Design, build, and deliver next-generation ECR sources aligned with Nuclear Science program needs.

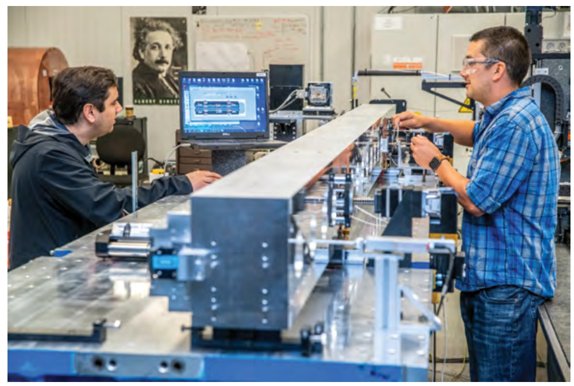
TEN-YEAR GOALS

- In partnership with the US Magnet Development Program (USMDP), develop novel superconducting and permanent magnet designs, technologies, and materials that will revolutionize DOE Office of High Energy Physics (HEP) collider capabilities and enable compact medical accelerators and light source performance beyond the current state-of-the-art.
- Develop next generation undulators for the ALS, the ALS-U, and other light sources.
- Provide engineering support for a national magnet development program for fusion, including high-temperature superconductors.

6.2.3 MAGNETICS ENGINEERING DEPARTMENT

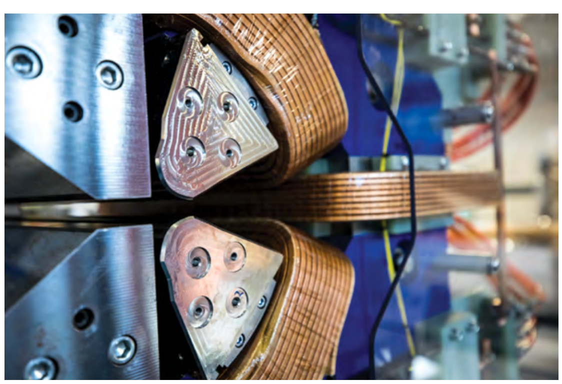
Advanced, high-performance magnets are keys to many sciences. The Magnetics Engineering Department has joined with the Accelerator Technology & Applied Physics (ATAP) Division to form the Berkeley Center for Magnet Technology (BCMT). The center serves Berkeley Lab and the larger DOE community as a full 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 a 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.



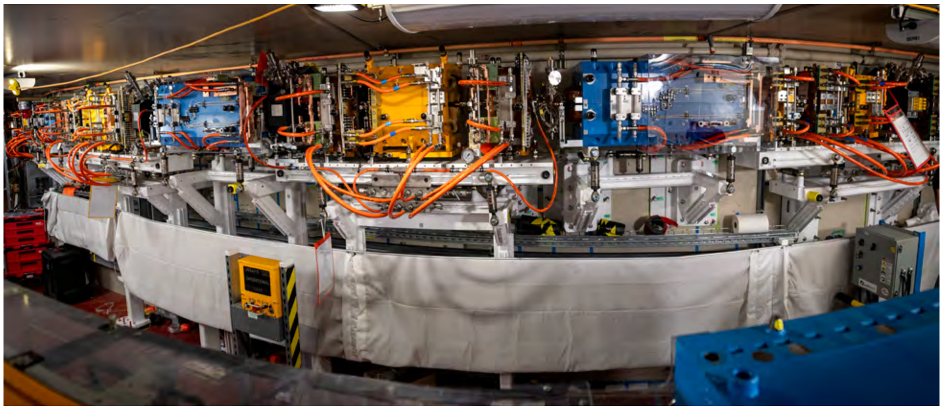
Kyle McCombs and Diego Arbelaez in EG's Undulator Measurement Facility (UMF), measuring the magnetic field on a hard x-ray undulator for the Linac Coherent Light Source. *Credit: Marilyn Sargent, Berkeley Lab*

A wide variety of superconducting R&D initiatives, including both materials and cabling technology development, along with delivered superconducting magnets, support current programs in the Nuclear Science Division and ATAP Division, as well as those of DOE sister and international Lab partners. BCMT combines an internationally recognized R&D component with the Engineering Division's core capabilities in magnet design, mechanical integration, fabrication, performance testing, and quality assurance.



Tunable combined function magnet prototype for the ALS-U.
Credit: Marilyn Sargent, Berkeley Lab

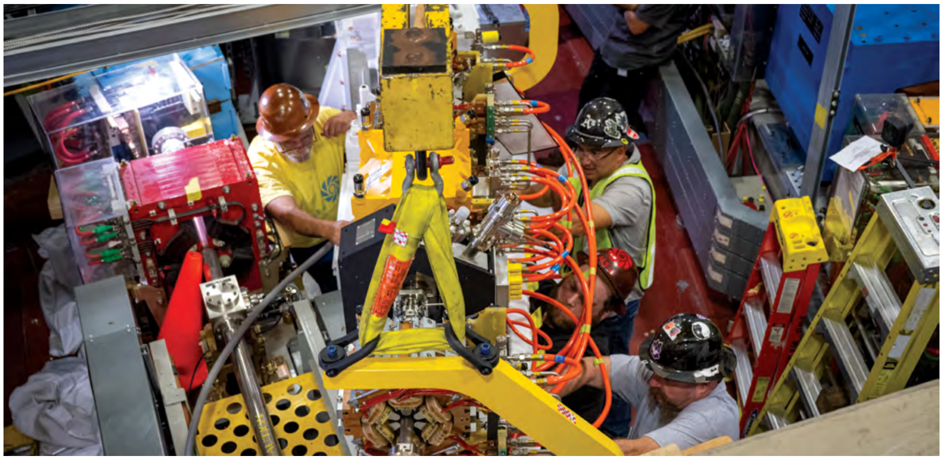
6.2.4 MANUFACTURING ENGINEERING DEPARTMENT



First accumulator ring sector installed in the ALS tunnel. *Credit: Thor Swift, Berkeley Lab*

Active manufacturing, production management, configuration control, and documentation management are mandated by the DOE as outlined in DOE Order 413.3b for projects and 414.1D for quality control. The Manufacturing Engineering Department provides the frameworks and tools for planning and executing science projects and programs throughout the lifecycle of a project or program in compliance with DOE directives. Core expertise areas are engineering tools, manufacturing engineering, and technical quality assurance.

We partner closely with the scientific division to support projects and programs to cover all aspects of manufacturing and quality engineers for planning, overseeing, and managing large-scale fabrications, assemblies, and installations.



Installation of the new accumulator ring in progress at the Advanced Light Source. *Credit: Thor Swift, Berkeley Lab.*

FIVE-YEAR GOALS

- Expand and standardize manufacturing quality support for electronics and electrical engineering projects.
- Continue to enhance and integrate our engineering processes with our Product Lifetime Management (PLM) systems in collaboration with the CAD department.
- Enhance technical procurements and vendor oversight capabilities.

TEN-YEAR GOALS

- Implement state-of-the-art manufacturing practices and tools; strengthen the connection with the technical QA group and processes.
- Strengthen manufacturing considerations as part of the design review process.

FIVE-YEAR GOALS

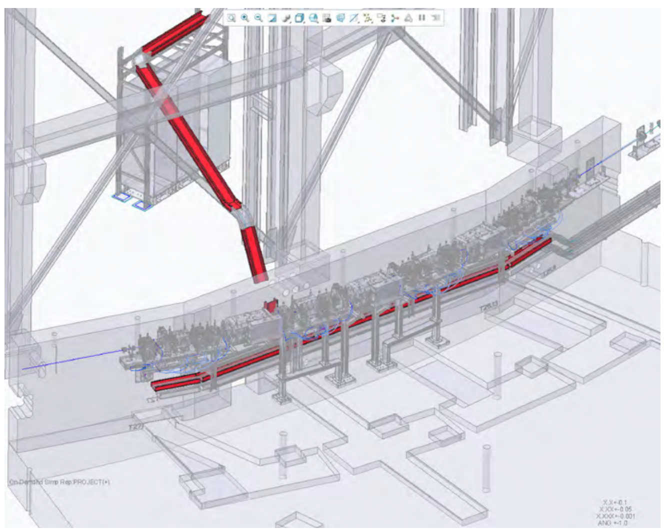
- Continue to enhance and integrate our engineering processes with PLM systems.
- Maintain and improve security and business continuity across the engineering software tools and servers.
- Provide mechanisms to further integrate software code via our gitlab.lbl.gov system with our engineering PLM system.
- Explore requirements management tools for engineering projects and implement the selected system.

TEN-YEAR GOALS

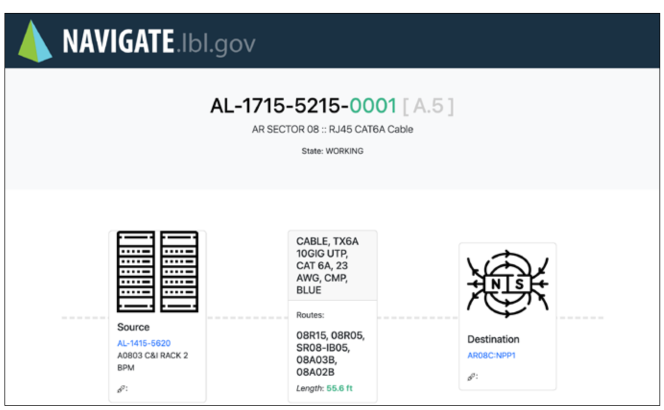
- Develop direct 3D modeling to fabrication capabilities and develop QA and manufacturing processes to support this approach.
- Develop CAD platforms that enable large-scale national and international collaborations.
- Explore automation of interference management in 3D systems.
- Establish the Navigate web portal as a centralized resource for quick access to information from various engineering databases.

6.2.5 COMPUTER AIDED DESIGN (CAD) DEPARTMENT

The Engineering CAD Department provides a platform for engineering processes for the division, our users, and their projects through a broad service catalog. Our suite of applications manages the life cycle of components from concept to installation and operations through decommissioning and obsolescence. In addition to managing the majority of project data for our partners through Product Lifetime Management (PLM) systems, we provide and support mechanical, electrical, and electronic CAD applications. The team deploys and maintains all engineering software, tools, and computing hardware required for the engineering workforce and the broader Berkeley Lab community. The Engineering CAD team develops and manages numerous web systems, databases and integrations that control engineering data for the Engineering Division and our partners.



CAD representation of an automated cable route to ease installation by installers, leveraging Creo Parametric, AutoCAD, Paneldes, and our own custom software. *Credit: Japie Arnold, Berkeley Lab*



Screenshot of a custom-developed cable management tool running on Navigate.lbl.gov that leverages live PLM (Windchill) data. *Credit: Samantha Gholba, Berkeley Lab*

6.2.6 PROJECT PLANNING AND CONTROLS DEPARTMENT

The Project Planning and Controls Department serves as a center for expertise in project planning and controls. It specializes in deploying the Lab's earned value management system (EVMS), which adheres to both ANSI/EIA-748 guidelines and DOE Order 413.3b, and ensuring that complex projects across Berkeley Lab have the most accurate performance measurement baseline from which to measure both cost and schedule performance.

Our team plays a pivotal role in furnishing a wide array of projects with dedicated project controls staff, establishing ourselves as the subject matter experts in areas such as EVMS, project controls, project management, risk management, and cost and schedule preparation for critical decision gate reviews. By integrating closely with project teams, we ensure the development and implementation of a project management control system aligned with Berkeley Lab's certified EVMS but also tailored to the unique demands of each project.

Members of the Engineering Division's Project Planning and Controls Department review project schedules. *Credit: Robinson Kuntz, Berkeley Lab*

FIVE-YEAR GOALS

- Benchmark project controls practices against best practices in the DOE complex and industry standards. Identify areas for further improvement and innovation.
- Integrate new software and tools to streamline processes, enhance collaboration, and improve decision-making on projects and reporting (e.g., advanced data warehouse modeling from enterprise EVMS for reporting and analysis, JIRA integration)
- Develop and implement a robust risk management program (strategies, tools, processes) to identify, assess, mitigate, and monitor project risks effectively.

TEN-YEAR GOALS

- Develop a comprehensive leadership succession plan to ensure continuity of leadership and expertise within the project controls department.
- Emerge as the definitive subject matter experts for all projects at Berkeley Lab that necessitate an integrated cost and schedule management system.

6.3 ENGINEERING CORE CAPABILITIES

6.3.1 ACCELERATOR ENGINEERING

Accelerator engineering is a core competency that supports the strategic goals of our partner divisions such as the BELLA Center and the ALS/ALS-U facility for the ATAP Division, and the 88-Inch Cyclotron, the EIC, and the Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) for the Nuclear Science Division. This area requires cross-functional teams with the science division partners to contribute expertise from all engineering departments following the traditions of the Berkeley Lab team science philosophy.

This core capability makes Berkeley Lab a key partner and international resource and technology leader in areas such as superconducting, resistive and permanent magnet systems design, ultrahigh vacuum technology, X-ray optics and beamline design, RF systems, diagnostics and instrumentation, and accelerator controls. Selected projects and areas are highlighted in sections 7.4 and 5.

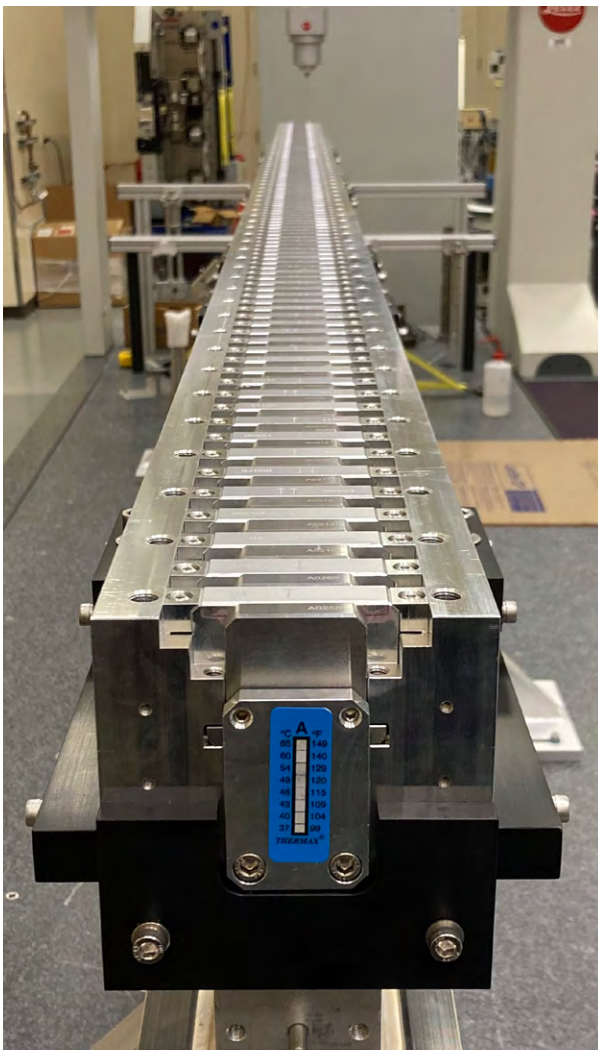
6.3.1.1 HIGH-LUMINOSITY LARGE HADRON COLLIDER (HL-LHC) ACCELERATOR UPGRADE PROJECT

In collaboration with the ATAP Division, we are designing, fabricating, and assembling the superconducting quadrupole magnets for the HL-LHC Accelerator Upgrade Project (see Section 5.3.1). The BCMT is responsible for providing the critical Nb3Sn cables and cold mass assembly. Together with our partners at Fermilab and Brookhaven National Laboratory, Berkeley Lab is responsible for completing the build of 24 4-meter-long Nb3Sn-based magnets. This will be the first major use of a high-field Nb3Sn superconductor in an accelerator.

Left, Katherine Ray, a Mechanical Engineer in the Survey & Alignment Group, takes the dimensional measurements of an LHC focusing magnet using the laser tracker system and a hand-held probe. Right, Ray takes the dimensional measurements of an LHC focusing magnet using the laser tracker system and a reflector. *Credit: Dan Cheng, Berkeley Lab.*

6.3.1.2 LINAC COHERENT LIGHT SOURCE II HIGH ENERGY (LCLS-II-HE) UPGRADE PROJECT

As a partner laboratory in a multilab collaboration, Berkeley Lab's ATAP and Engineering Divisions made several major contributions to the construction of the LCLS-II at the SLAC National Accelerator Laboratory. The LCLS-II-HE project is now underway at SLAC to upgrade the LCLS-II facility. Berkeley Lab is responsible for the design and procurement of undulator components required for the LCLS-II-HE upgrade. Berkeley Lab is also contributing to the LCLS-II-HE project in-beam dynamics modeling and LLRF control systems.



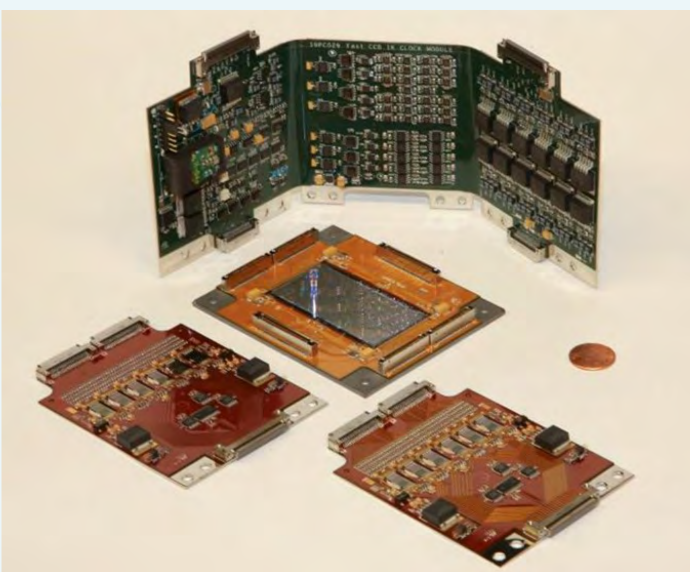
The magnetic structure for LCLS-II-HE FEL undulator being prepped for integration into the support structure.
Credit: Diego Arbelaez, Berkeley Lab

6.3.2 DETECTOR SYSTEMS

Detector systems are key components to many of the science programs at Berkeley Lab. As with accelerator technology, forming multidisciplinary teams with our scientific partner divisions is essential to developing cutting-edge and innovative detector systems from micro-scale to large-scale devices.

In partnership with the Physics, Nuclear Science, and ATAP Divisions, and the ALS, the Engineering Division designs and builds detector systems based on semiconductor technologies. We develop large-scale systems for detectors at high-energy physics colliders to precision devices at light source beamlines. In disciplines ranging from nuclear science to biology, detectors enable experiments to produce data. Integrating expertise in large-scale systems with deep competencies in the 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.

The Engineering Division is a worldwide leader in developing advanced composite extreme low-mass structures to build large-scale detectors such as ATLAS, and future detector structures for the Electron-Proton/Ion Collider (ePIC), the Electron-Ion Collider (EIC), and an upgrade to the inner tracking system of A Large Ion Collider Experiment (ALICE ITS3) at CERN (the European Organization for Nuclear Research).



Charge-coupled devices (CCDs) and custom IC-based camera for very high-speed imaging applications focused for soft X-ray microscopy. *Credit: Nord Andresen, Berkeley Lab*

ATLAS UPGRADES FOR THE HL-LHC

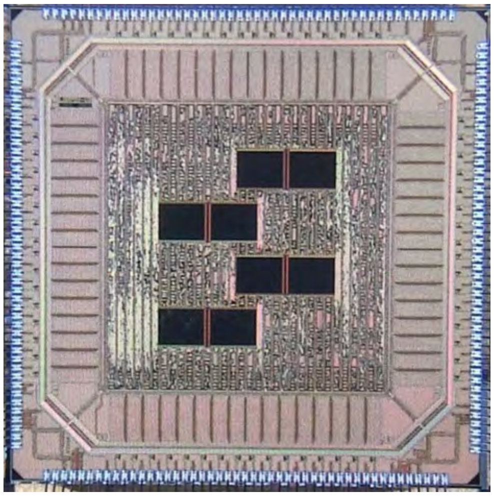
Members of Berkeley Lab's Engineering and Physics Divisions are making significant contributions to the ATLAS Experiment, part of the Large Hadron Collider's high-luminosity upgrade (HL-LHC) at CERN, including the design and fabrication of crucial new detector structures, as well as the development of next-generation pixel detector and readout chip technology and staves and strip detector technology.

6.3.2.1 DEEP UNDERGROUND NEUTRINO EXPERIMENT (DUNE) NEAR DETECTOR

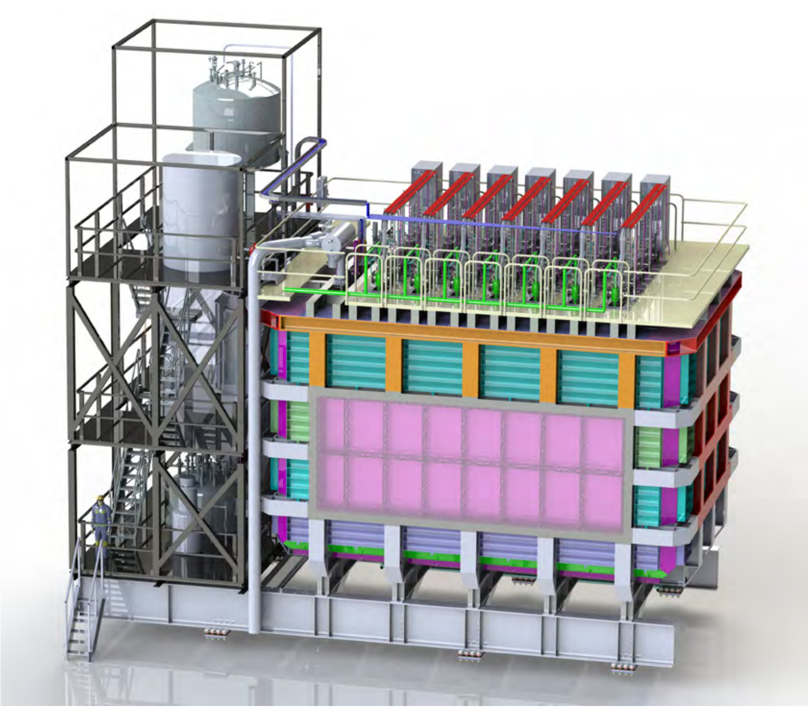
DUNE is a next-generation neutrino experiment that is executed by an international multilab collaboration. Learn more about the Physical Science Area's efforts for DUNE in Section 3.2.2.

The Engineering Division's electrical engineers are contributing novel cryogenic charge readout electronics to the DUNE Collaboration, and over the next few years will produce more than 14 million channels of low-noise readout for the DUNE Near Detector.

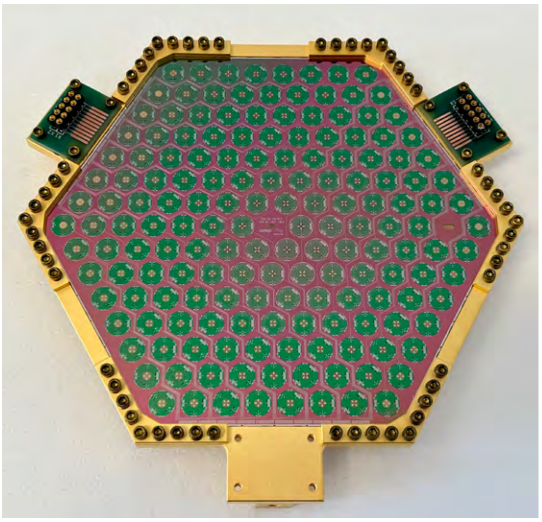
The Engineering Division's mechanical engineers are leading the design and development of the membrane cryostat that will house the ND-LAr detector, providing containment for ~300 metric tons of high-purity liquid argon. Our mechanical engineering team is also coordinating the systems engineering, integration, and installation efforts for the entire Near Detector system, which includes a muon spectrometer and a beam monitor in series with the ND-LAr detector, and the ability for the detectors to travel 30 meters on- and off-axis weekly.



Microphotograph of custom LArPix (liquid argon pixel) integrated circuit for cryogenic neutrino detection. Recipient of the 2022 R&D 100 Award. *Credit: Phathakone Sanethavong, Berkeley Lab*



CAD representation of the liquid argon cryostat for the ND-LAr. A team of engineers and scientists in these divisions has also conceived, developed, and built LArPix, a prototype 3D pixelated detection system for DUNE. *Credit: Andrew Lambert, Peter Tennessen, Berkeley Lab*



A detector array for the CMB-S4 project, designed by Berkeley Lab and fabricated by SEEQC, Inc.
Credit: Aritoki Suzuki, Berkeley Lab

6.3.2.2 COSMIC MICROWAVE BACKGROUND STAGE 4 PROJECT (CMB-S4)

In partnership with the Physics Division, the Engineering Division is supporting the groundbreaking CMB-S4 project (see Section 3.2.6), which brings together a US-led collaboration of cosmologists, data scientists, physicists, integrated circuit designers, and engineers working to deploy the most extensive array of ground-based CMB telescopes ever built. The recently proposed astronomical survey experiment plans to incorporate on the order of 10 times more detectors than any current CMB experiment and is designed to cross critical thresholds in confining cosmological models. CMB-S4 aims to directly measure the imprint of quantum gravitational waves generated during the primordial inflationary phase of the universe.

The Engineering Division is involved in the technical development of major subsystems, including the cutting-edge microwave detectors utilizing superconducting integrated circuits and the small aperture telescopes optimized to detect the large-angular scale polarization signals imprinted during the dawn of time.

6.3.2.3 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 more than 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 and transferred the technology to industry, which has commercialized a complete transmission electron microscopy (TEM) imaging sensor system. The Engineering Division's development of the next generation of CMOS imagers will enable significant further improvement in electron microscopy.

Newly developed charge-coupled devices (CCDs) and associated readout algorithms, together with custom ASICs, will provide cameras for very high-speed imaging applications such as soft X-ray microscopy.

6.3.2.4 CUSTOM INTEGRATED CIRCUITS OPEN THE PATH TO HIGH-PERFORMANCE DETECTOR, COMPUTING, AND IMAGING DEVICES

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

The division's core capabilities include ultra-low-noise analog front ends, high-performance data converters, circuits for precision timing and data acquisition, and CCD 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 16 nanometers.

6.3.2.5 FUTURE DIRECTIONS FOR DETECTOR READOUT ELECTRONICS

The Engineering Division'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 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. One benefit to Berkeley Lab is open-source embedded FPGA technology that will enable the realization of single-chip detector front ends incorporating data reduction and pre-processing. Meanwhile, the capabilities of commercial off-the-shelf modules are expanding while their costs go down. Another example is the increasing impact of AI and ML techniques in detector operation and design. These trends will drive the future development of scientific instrumentation.

6.3.3 FABRICATION AND MANUFACTURING ENGINEERING

The fabrication and shop facilities focus on providing a broad range of comprehensive, technically advanced manufacturing resources to the scientific divisions and user facilities of Berkeley Lab with technical capabilities often not available from commercial vendors. In addition, the onsite shops allow for quick turnaround and collaborative process development for novel components.

6.3.3.1 COMPOSITES ENGINEERING

The Composites Shop specializes in designing and fabricating high-performance carbon-fiber structures and precision-bonded assemblies (incorporating both metallic and composite components) for silicon tracking detectors and other specialized applications. We have provided global support and integrated low-mass cooling support for detecting elements for various silicon trackers for DOE's Offices of High Energy Physics and Nuclear Physics, installed around the world. The latest efforts are for the ATLAS Inner Tracker (ITk) upgrade. We have started preliminary work on ePIC, an EIC detector at Brookhaven National Laboratory, and ALICE ITS3, a future upgrade for ALICE at CERN.

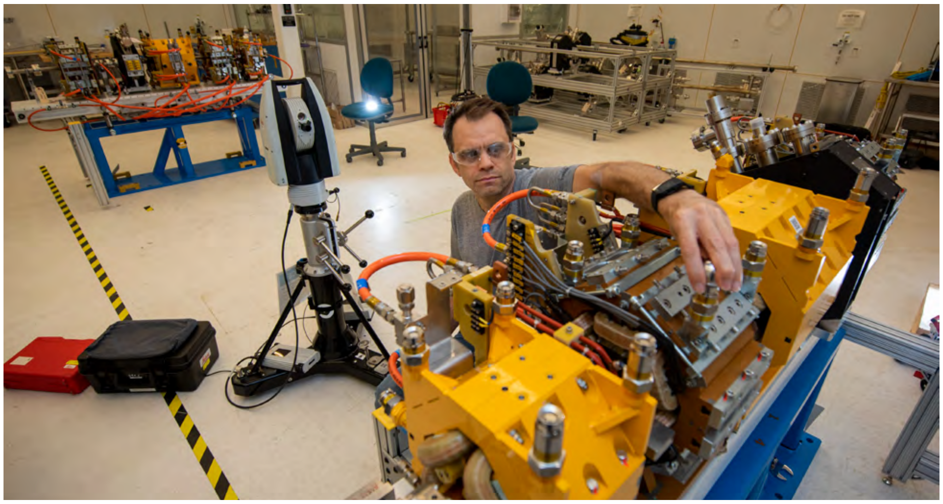
The Composites Shop works closely with the Engineering Division's fabrication and precision metrology and survey capabilities to design and fabricate the molds and precision assembly tooling required to build these structures.

Richard Breese makes adjustments to a structural bulkhead as it is dry fitted to the ATLAS ITk outer cylinder's forward section. *Credit: Todd Claybaugh, Berkeley Lab*

6.3.3.2 PRECISION METROLOGY, SURVEY, AND ALIGNMENT

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

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



Chris Hernikl, an ALS mechanical engineering technician, works on the precision alignment of ALS-U accumulator ring components. *Credit: Thor Swift, Berkeley Lab*

6.3.3.3 MANUFACTURING ENGINEERING

Key areas of competency for our manufacturing engineering team are installation planning and final assembly coordination, which are critical functions for science projects. Our engineers support the technical teams and technical procurement specialists by defining and overseeing the execution of large-scale installation efforts, such as the ALS-U, or complex component fabrication at outside companies to ensure integration and functionality of the technical delivery. They work closely with our quality assurance engineers to track quality issues and improve fabrication, assembly, and installation processes.

6.3.3.4 MACHINE AND ASSEMBLY SHOPS

The manufacturing and assembly facilities focus on providing a broad range of technically advanced production resources to the scientific divisions and user facilities of Berkeley Lab. This resource provides a collaborative environment for the development of components and assembly, in-house fabrication of complicated, multi-process, multilevel assemblies, shorter lead times than outside vendors, emergency fabrication, and repair. This branch of engineering includes a central manufacturing center with unique machining centers—e.g., a large-format waterjet, a computer numerical control machine (CNC), and a coordinate measurement machine (CMM)—auxiliary shops distributed across Berkeley Lab (for rapid prototyping, repair, and tooling fabrication), a general assembly shop with a wide range of features such as clean rooms and high bay capacity, and an array of specialized shops such as the Composites Shop and the superconducting magnet winding facility.

Finished 16-inch C18150 copper alloy vacuum chamber for the ALS-U. *Credit: Rick Kraft, Berkeley Lab*

A key technology for future generation light sources is ultra-high vacuum (UHV) technology based on non-evaporable getter (NEG) coating and vacuum component engineering and fabrication where the Engineering Division has cutting-edge engineering and manufacturing capabilities.

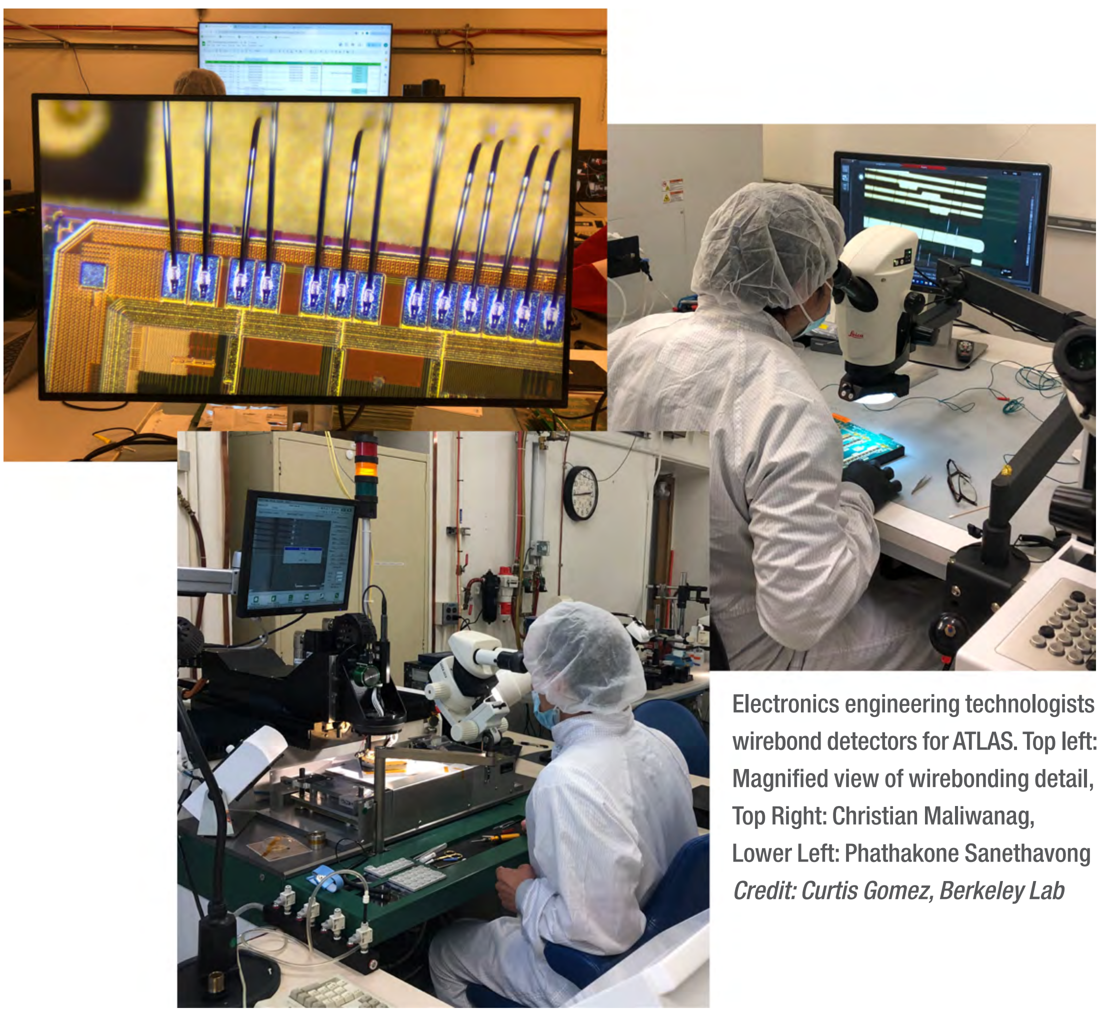
Main floor of the Engineering Division's mechanical fabrication facilities. *Credit: Rick Kraft, Berkeley Lab*

6.3.3.5 ELECTRONIC SHOPS AND LABORATORIES

The electronics engineering technologist shops and laboratories offer a comprehensive array of services to support engineers, researchers, and scientific projects within Berkeley Lab.

The electronics maintenance and electronics installation shops provide qualified electrical workers who deliver round-the-clock operations and user assistance, spanning a diverse spectrum of technologies including controls, RF, and high-power electronics crucial for photon science activities.

In other areas, fabrication technologists facilitate design support ranging from chassis construction to intricate microscopic wire bonding of semiconductor devices, catering to the various project requirements across Berkeley Lab. The semiconductor processing facility specializes in fabricating various types of radiation detectors that support electronics R&D and detector and accelerator engineering.



Electronics engineering technologists wirebond detectors for ATLAS. Top left: Magnified view of wirebonding detail, Top Right: Christian Maliwanag, Lower Left: Phathakone Sanethavong *Credit: Curtis Gomez, Berkeley Lab*

6.3.4 PROJECT EXECUTION

Berkeley Lab's tradition and culture of team science fosters a close link between scientific experts and engineering professionals skilled in transitioning novel ideas into complex experimental instruments. The Engineering Division supports scientific projects during their early phases by developing conceptual designs and setting up adequate project management systems. The Engineering Division has unique expertise in staffing key project management, systems engineering, manufacturing, and QA engineering roles. The division's matrix system allows for allocating resources in a timely and flexible fashion as projects evolve through their lifecycle.

6.3.4.1 PROJECT MANAGEMENT

As scientific effort continues to become increasingly more projectized, the Engineering Division fosters the development of a cadre of core project management experts skilled in navigating all project lifecycle phases for all sizes of projects. The Engineering Division's project managers adhere to the DOE 413.3B Order requirements for project execution and are commonly Project Management Institute certified. The division grows future project managers by first exposing lead engineers to control account manager roles of individual subsystems within a large project. As a next step, engineers become project managers of smaller-scale projects, and ultimately managers of large or mission-critical projects.

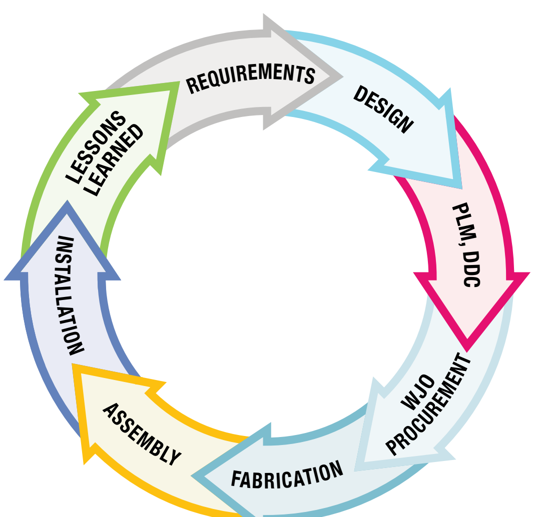


Illustration showing the project lifecycle management framework supported by the CAD Department.
Credit: CAD Department

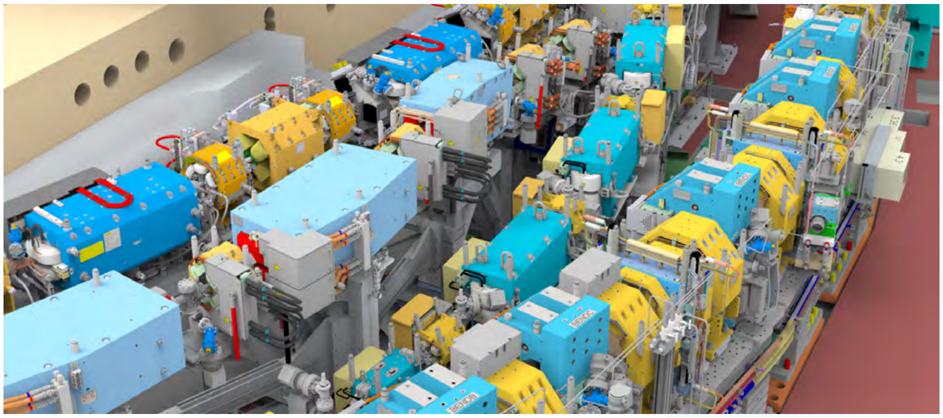
6.3.4.2 SYSTEMS AND INTEGRATION ENGINEERING

The systems engineering approach to the management of technical work enables successful technical completion of complex scientific construction projects, particularly those with deliverables from disparate groups, institutions, or even nations, as is typical of many Berkeley Lab projects. The Engineering Division's systems engineers are experts at flowing down detailed technical requirements from the high-level scientific objectives of an experiment, defining interfaces between deliverables from different groups, and ensuring ultimate science performance through the verification and validation process. The Mechanical Engineering Department supports the integrated design of large projects. This involves the coordination of design activities at the interface between major subsystems. This holistic technical management approach facilitates a successful installation and ensures that the system will function as a single coherent integrated unit.

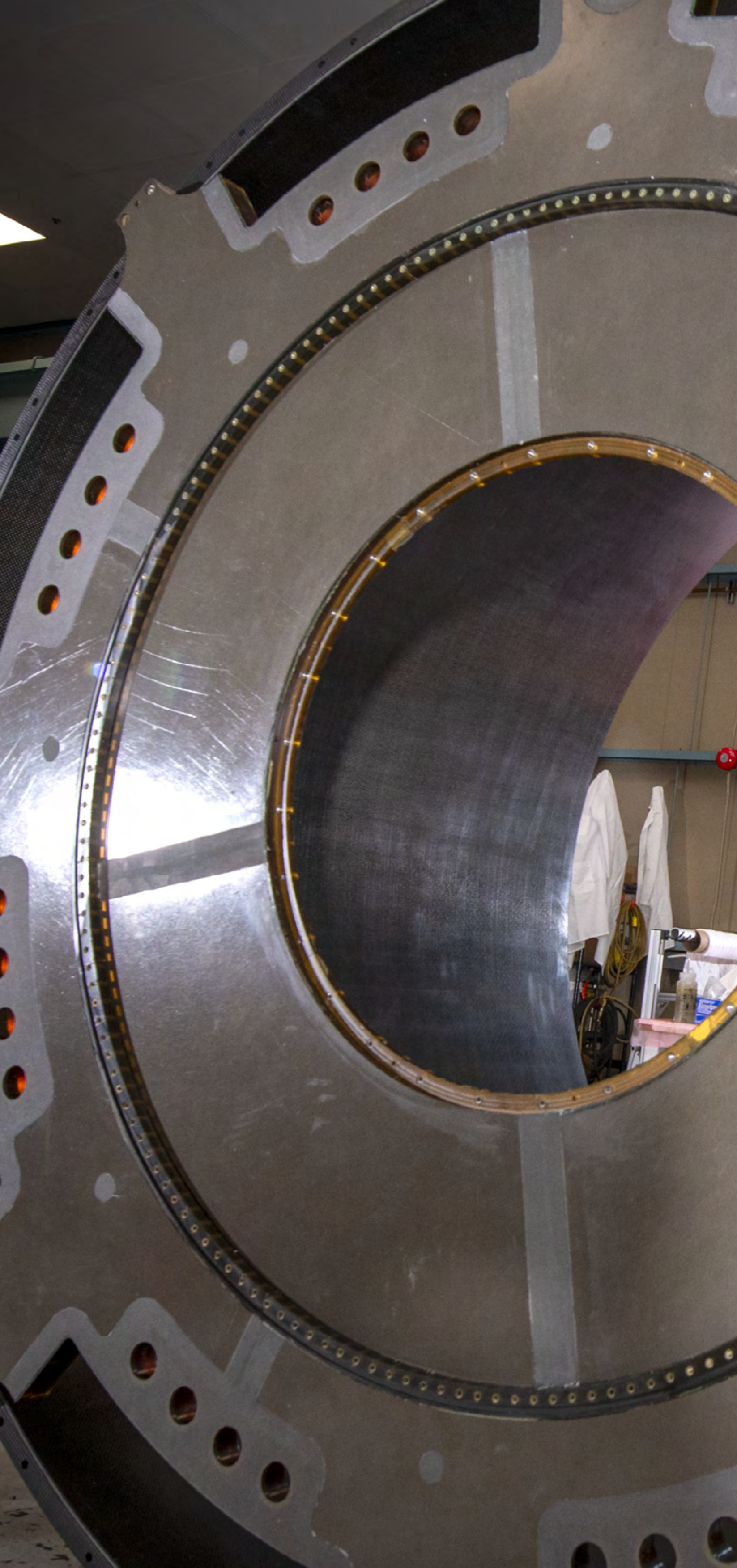
6.3.5 ENGINEERING SOFTWARE, CAD, AND SYSTEMS TOOLS

The Engineering CAD Department is a core function of the division, providing cross-functional support across the Physical Science Area and our Lab-wide partner divisions by working closely with Berkeley Lab's Information Technology Division and the Office of the Chief Financial Officer. The department provides and develops tools for mechanical and electrical design and analysis software, hardware support, quality assurance, workflow process development, and data management services that provide an essential framework for managing projects of all sizes, including document and configuration management and industry-standard CMII change control. Berkeley Lab's Document Control Center houses a repository of more than 350,000 records dating back to the early 1940s. Our Windchill PLM system helps engineers realize our digital twin concept, which associates a virtual representation of physical components within the Windchill database to allow for effective change and service lifecycle management.

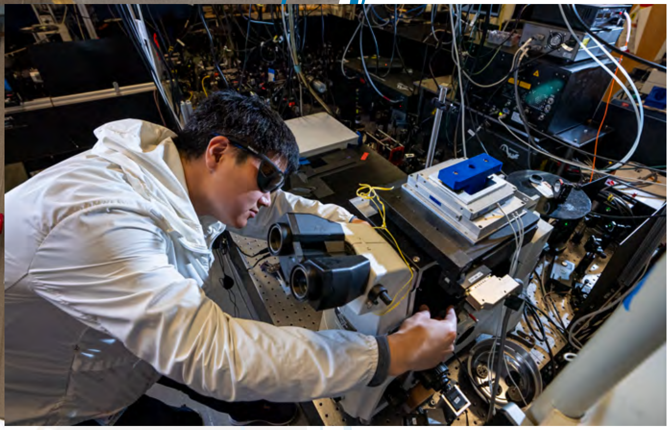
Our service catalog spans a wide range of software applications and layers of customization to shepherd controlled data through their service life. Supported software and systems include electronic and mechanical applications and licensing, finite element analysis software, product lifecycle management systems (e.g., Windchill), Berkeley Lab's official Document Control Center, the Web Job Order (WJO) system, Navigate.lbl.gov, and Berkeley Lab's Work Breakdown Structure (WBS) Dictionary tool, among others. The team maintains and provides computing resources, backups, large-format printing, network file storage and sharing, remote computation servers, account management, web presence, and cloud services. All of our services run atop a virtual cloud infrastructure to facilitate site-wide and remote access. In addition, the CAD Department provides numerous training classes and tutorials on the use of these engineering tools and their processes.



CAD illustration of the ALS-U transfer line region utilizing Creo Parametric 3D modeling and Keyshot rendering. *Credit: Japie Arnold and James Osborn, Berkeley Lab CAD Department*



Building 59, home of the National Energy Research Scientific Computing Center (NERSC). *Credit: Roy Kaltschmidt, Berkeley Lab*



Postdoctoral researcher Xiao Qi in the laser room at the Molecular Foundry at Berkeley Lab. Qi used the setup to develop a new optical computing material from nanoparticles that exhibit a phenomenon known as “photon avalanching,” in which a small increase in laser power results in a giant, disproportionate increase in the light emitted by the nanoparticles. Credit: *Marilyn Sargent, Berkeley Lab*

Accumulator ring sector installed in the ALS tunnel.
Credit: Thor Swift, Berkeley Lab

One component of the ATLAS Detector carbon fiber cylinder is lifted into place as it is being assembled at Berkeley Lab. *Credit: Thor Swift, Berkeley Lab*

7. CROSSCUTTING CAPABILITIES

Breakthrough science does not happen in isolation. It is powered by cutting-edge tools and technologies that push the boundaries of discovery. From artificial intelligence (AI) and machine learning (ML) to microelectronics, quantum information science (QIS), and light source facilities, these crosscutting capabilities are transforming the way we do fundamental basic research in the Physical Sciences Area. This section serves as both a reference and a roadmap for ongoing and future initiatives for these powerful capabilities.

7.1 ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

AI and ML are a set of tools for automating any task where the input and output can be represented in a format understandable by a computer. Such tasks range from experimental design to data analysis and machine control, and the formats include images, sequences, and other numeric representations. AI/ML is revolutionizing the way that we interact with each other and the world around us, and AI/ML for the physical sciences is no exception. Researchers across the Physical Sciences Area are integrating state-of-the-art methods into their workflows, extending the scientific potential of our programs. We also have a number of scientists who are actively developing new or modified AI/ML methods to address unique challenges in AI/ML for the physical sciences, including how best to combine high-fidelity, ab initio simulations with experimental data.

Researchers have developed core strengths in several key areas, often through cross-division collaboration. Examples of these efforts, as noted in the division sections, highlight the collaborative and interdisciplinary nature of our AI/ML research.

7.1.1 SURROGATE MODELING

An AI/ML model can be trained to predict the behavior of a physical system, like a particle accelerator, based on numerical simulations of that system. After training, this surrogate model can be used instead of the original simulations at a fraction of the computational cost. For example, researchers use surrogate modeling to design and optimize advanced particle accelerators and detectors (e.g., with Bayesian optimization), as well as for fast-executing models that replace computationally expensive plasma accelerator simulations.

7.1.2 SIMULATION-BASED INFERENCE

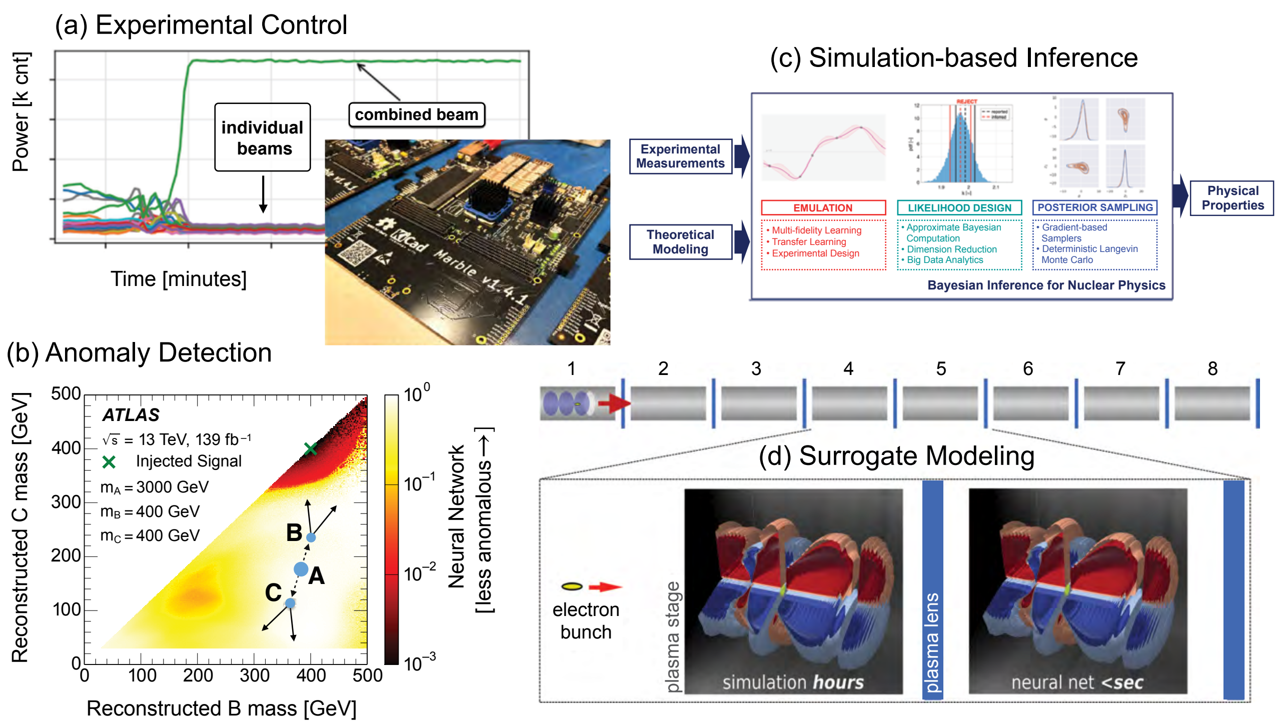
High-fidelity simulations are a defining feature of Physical Sciences Area research, and AI/ML can be combined with these tools to use all available information in our complex data. AI/ML methods automatically identify useful features and guide the search for the best physics model parameters to describe the data, along with the corresponding uncertainties. Applications include cosmology, particle physics, and relativistic nuclear physics. For example, ML-based tools are required to solve the computationally intensive problem of deducing parameters of complex theoretical models from complex and heterogeneous data (the "inverse problem"), which pervades experimental science. An essential element to interpret such solutions is an assessment of their accuracy or uncertainty. Researchers are developing and implementing general AI/ML approaches to solving the Inverse Problem with quantifiable uncertainty in several research areas: measurements of the mass and fundamental nature of the neutrino; study of the Quark-Gluon Plasma that filled the early universe; and mapping of natural and anthropogenic radiation environments.

7.1.3 ANOMALY DETECTION

AI/ML methods can identify rare, unexpected behaviors (anomalies) in large quantities of multidimensional data. Physical Sciences Area researchers use these anomaly detection protocols for quality control (e.g., quenches in superconducting magnets or noisy channels in particle detectors), to search for new, fundamental particles, and to detect weak radiological/nuclear signatures in complex backgrounds for nuclear nonproliferation applications. For example, Physics Division researchers have developed new AI/ML-powered anomaly detection methods and are deploying them to data from a diverse set of experiments. A recent analysis from the A Toroidal LHC Apparatus (ATLAS) experiment at CERN (the European Organization for Nuclear Research) showed that the anomaly detection strategy significantly increased the breadth of the search while preserving competitive depth with classical approaches. Running this strategy was computationally challenging, requiring the training of tens of thousands of neural networks to achieve sensitivity and stability.

7.1.4 EXPERIMENTAL CONTROL

All other examples deal with the offline application of AI/ML, where latency is not a critical concern. When operating complex scientific facilities, scientists need to interact with instruments and data in real time and make fast decisions about operational conditions as well as about which data to keep. AI/ML algorithms can provide faster, more reliable, and more powerful controls than traditional approaches. Advances from AI/ML include facilitating better and faster decisions made by triggering systems at a number of experiments and optimizations of beams in a variety of facilities. For example, researchers have demonstrated that a neural network can be trained (in situ) as a pattern recognizer, to deterministically stabilize a multiway coherent laser combiner, with a significantly improved precision at maximum combining efficiency. Such AI/ML controllers are running in our field-programmable gate array (FPGA) platforms for complex, real-time, adaptive, precise steering of high-power lasers, such as those at the Berkeley Lab Laser Accelerator (BELLA) Center. They are also running in superconducting radio frequency (RF) cavity accelerators—such as those being installed at the Linac (linear accelerator) Coherent Light Source II High Energy (LCLS-II-HE) Upgrade Project at the SLAC National Accelerator Laboratory, and the Proton Improvement Plan II (PIP-II) at Fermi National Accelerator Laboratory (Fermilab)—to solve complex problems in feedback control.



Examples for each of the key areas, highlighting research across all four divisions of the Physical Sciences Area. (a) An example of experimental control from the Engineering Division, where ML controllers are deployed in firmware (bottom right) to combine multiple lasers into a single, powerful beam (upper left). (b) An example of anomaly detection from the Physics Division, where ML tools automatically identify patterns in many features at the same time that are inconsistent with the Standard Model. (c) An example of simulation-based inference in the Nuclear Science Division, where ML tools are being used to optimally infer parameters from complex datasets. (d) An example of surrogate modeling modeling from the Accelerator Technology & Applied Physics (ATAP) Division, where ML models can rapidly emulate the physics of particle accelerators. *Credits: Peter Jacobs, Axel Huebl, Jean-Luc Vay, and Ben Nachman*

7.1.5 SYNERGIES WITH LAB-WIDE COMPUTING

The Physical Science Area has built strong collaborations with the Computing Science Area to address foundational challenges in scaling AI/ML methods for real-world applications. The Perlmutter supercomputer at Berkeley Lab's National Energy Research Supercomputing Center (NERSC) is a hybrid machine with a large number of state-of-the-art GPUs critical for AI/ML. Researchers in the Physical Sciences Area also contribute to the efforts of NERSC and the Energy Sciences Network (ESnet) to build a "superfacility" that integrates data, simulations, and AI/ML in the same place and with real-time capabilities.

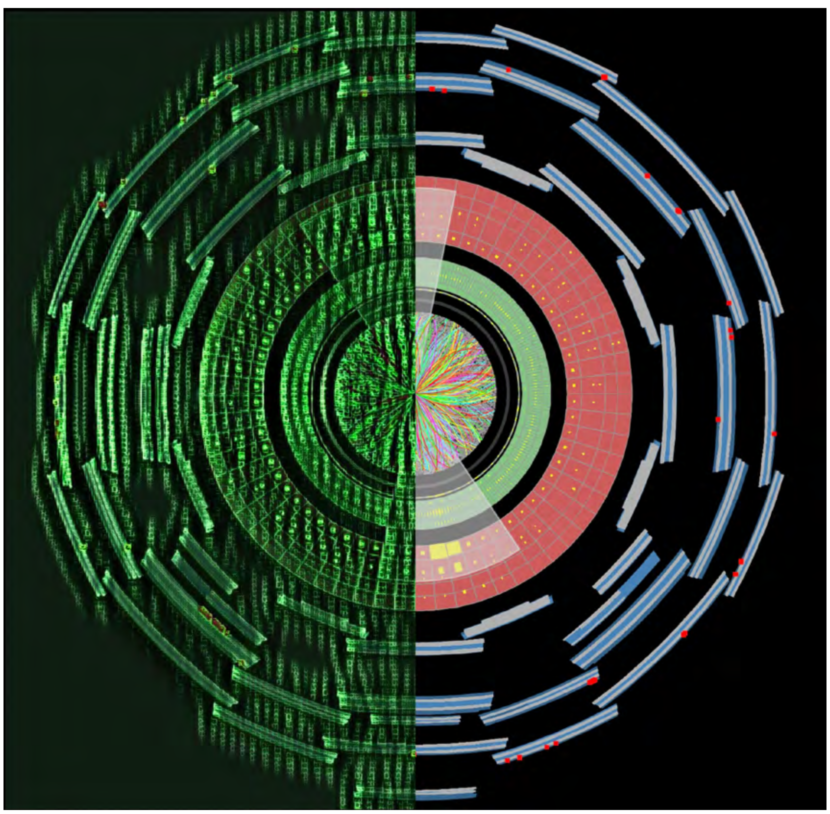
Photo of the Perlmutter supercomputer at NERSC, which has enabled AI/ML at scale with nearly 10,000 state-of-the-art graphics processing units (GPUs). *Credit: Thor Swift, Berkeley Lab*

7.1.6 A CROSSCUTTING INITIATIVE

A new group hosted by the Physics Division, with broad participation from across the Physical Sciences Area, seeks to connect scientists developing, adapting, and deploying AI/ML solutions to area research. This Machine Learning for Fundamental Physics Group hosts seminars, training events, and other activities to catalyze and extend research and to build community across Berkeley Lab and with the University of California, Berkeley, campus, notably through the Berkeley Institute for Data Science (BIDS).

7.1.7 KEY GOALS

Over the next several years, Physical Sciences Area researchers will continue to develop expertise and train the next generation of researchers in our areas of core competency. We will respond to the rapidly changing landscape of AI/ML, seeking out new opportunities to enhance our science potential. A key theme will be unifying simulations and data with AI/ML. Tighter, real-time connections of experiments and simulations will guide experimental campaigns and control accelerators. Simulations with embedded AI/ML components or simulations embedded within an AI/ML model will allow for faster, more powerful statistical analysis. Berkeley Lab will continue to be a center for scholarship and training at the intersection of AI/ML and physics.



AI/ML is transforming many facets of work in the Physical Sciences Area. The picture shows a display of a proton-proton collision event at the Large Hadron Collider as reconstructed in the ATLAS detector. Almost every aspect of the reconstruction, interpretation, and simulation of those events has been aided by a variety of ML techniques. *Original event display from the ATLAS Experiment at CERN*

7.2 MICROELECTRONICS

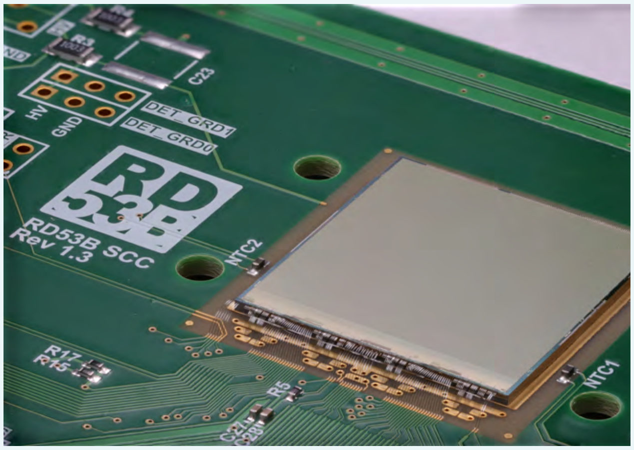
Microelectronics developed by Physical Sciences Area scientists and engineers have enabled particle detectors for decades. These microelectronics include the first complementary metal-oxide-semiconductor (CMOS) integrated circuit, developed for the worldwide high-energy physics community in 1986, and instrumentation for the next generation of accelerator facilities: the inner tracking layer of the ATLAS detector at CERN and the three-layer Monolithic Active Pixel Sensors (MAPS) tracker for the Electron-Ion Collider (EIC). These microelectronics have been instrumental in the discovery of the top quark and the Higgs boson, enhancing the capabilities of the world's most powerful electron and X-ray microscopes, and unlocking the mysteries of the neutrino.

Through close collaborations between the Physics, Nuclear Science, and Engineering Divisions, and other labs and universities including CERN and the High Energy Physics Integrated Circuit Design Consortium (HEPIC) member institutes, Berkeley Lab has developed and maintained world-class capabilities particularly in design for radiation tolerance and cryogenic compatibility.

7.2.1 RADIATION-TOLERANT MICROELECTRONICS FOR DETECTOR READOUT

Radiation-tolerant microelectronics are key enabling components of modern particle detectors. Berkeley Lab has more than 30 years of experience developing custom radiation-tolerant integrated circuits. This unique capability has been leveraged over multiple experiments and detector systems from the ATLAS detector at CERN to image sensors for electron microscopy. Recently, as part of the worldwide RD53 Collaboration (CERN's fifty-third research and development [R&D] program, which develops pixel readout integrated circuits for extreme rates and radiation), Berkeley Lab helped deliver the next iteration of the Inner Tracker pixelated detector chip (ITkPixV2), the most radiation-tolerant integrated circuit for particle physics detectors to date, with tolerance in excess of one gigarad. ITkPixV2 includes a Berkeley Lab-developed analog front end and will be incorporated into the new Inner Tracker (ITk) of the ATLAS Experiment for the Large Hadron Collider (LHC) High-Luminosity Upgrade.

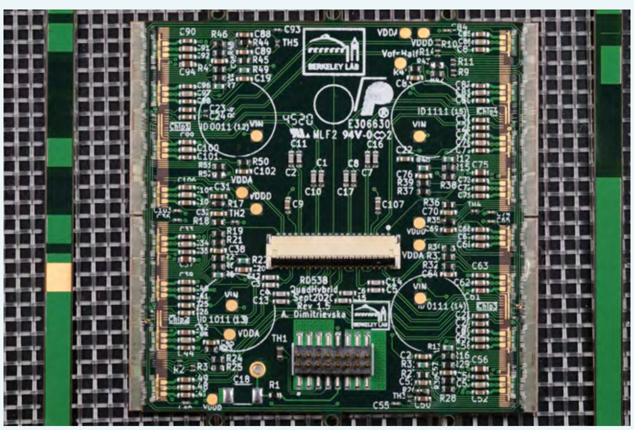
Continuing at the forefront of radiation-tolerant design for particle trackers, Berkeley Lab researchers from multiple Physical Sciences Area divisions have delivered a prototype integrated circuit in advanced 28 nm CMOS technology for the next generation of pixel detectors. This novel integrated circuit will provide the timing capability required to enable future four-dimensional trackers.



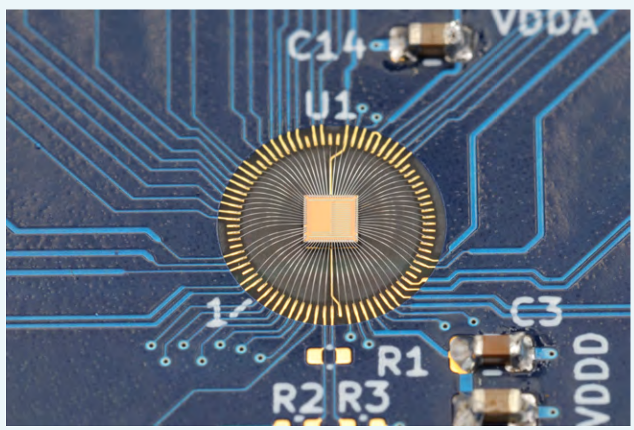
Photograph of an ITkPixV2 die, including the Berkeley Lab-designed analog front end, wire bonded to a printed circuit board. ITkPixV2 is the most radiation-tolerant integrated circuit ever constructed. *Credit: Timon Heim, Berkeley Lab*

RADIATION EFFECTS EVALUATION AND RADIATION-TOLERANT DESIGN

Berkeley Lab has been deeply involved in the radiation effects field since the 1960s, when NASA and Berkeley Lab staff used the 88-Inch Cyclotron to evaluate radiation tolerance of components for the Apollo Program. The Berkeley Accelerator Space Effects (BASE) Facility, operated by the Nuclear Science Division, remains at the forefront of radiation component testing for the national security space community.



ITkPixV1 Quad Module. Four chips are connected to one sensor tile (4cm by 4cm) onto which a flexible printed circuit board is glued to connect to power and data services.
Credit: Timon Heim, Berkeley Lab



Photograph of "Pebbles," a low-noise, low-power, radiation-tolerant prototype integrated circuit for next-generation 4D detector readout that will provide unprecedented timing performance. *Credit: Timon Heim, Berkeley Lab*

The close collaboration between the different divisions in the Physical Science Area has been key to the successful deployment of advanced custom electronics in advanced detector systems. For example, Berkeley Lab advances in carbon composites for detector supports, flex layouts, system integration, and detector assembly techniques have enhanced Berkeley Lab-developed microelectronics' impact on the international science community.

7.2.2 CRYOGENIC ELECTRONICS: ENABLING A NEW CLASS OF DETECTORS

Berkeley Lab maintains a strong program in cryogenic electronics. Microelectronics operating in cryogenic environments are essential to providing optimized performance when reading out cryogenic detector systems, such as liquid noble time projection chambers for neutrino and double beta decay experiments and dark matter searches, and deep cryogenic superconducting sensors, such as transition-edge sensors.

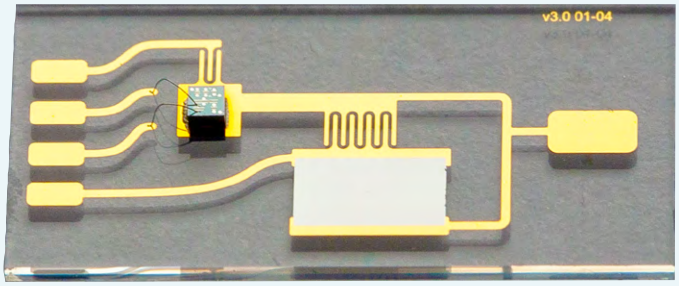
Microelectronics developed at Berkeley Lab have played important roles in several experiments operating at liquid argon temperature (87 K), such as the Deep Underground Neutrino Experiment (DUNE) Near Detector and Far Detector and the Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay (LEGEND) detector. In addition, Berkeley Lab is investigating the application of custom microelectronics to the readout of superconducting sensors at deep cryogenic temperatures. An example is a prototype calorimeter operating successfully at 100 mK. Another example is the development effort on graphene field-effect transistors as a class of transformative electronic devices for radiation detectors and quantum sensors. Cryogenic electronics can also be used for readouts, analysis, and decision-making in cold diagnostics for superconducting magnets or for QIS systems. Furthermore, cryogenic power electronics such as metal–oxide–semiconductor field-effect transistors (MOSFETs) are rapidly developing, opening new avenues to active current control and distribution in magnets.

7.2.3 BEYOND MOORE'S LAW MICROELECTRONICS

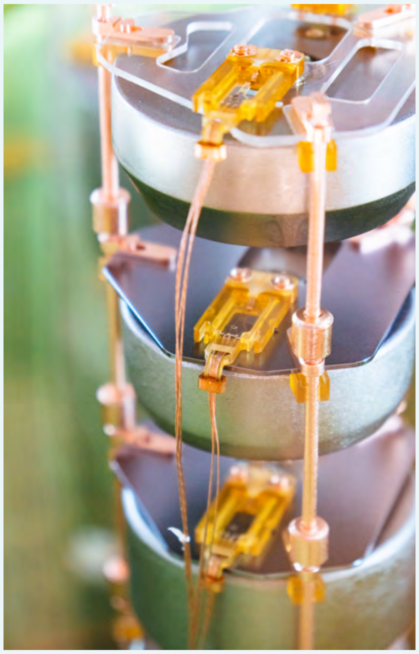
Berkeley Lab is exploring microelectronic systems beyond the standard CMOS technology, which has reliably experienced improved performance over time through Moore's Law. Research teams spanning many Berkeley Lab divisions and partner institutions are investigating different approaches to microelectronic system design, such as co-design with new materials and CMOS post-processing for imaging applications. We are beginning to explore superconductor materials for low-power circuits in deep cryogenic temperatures.

LOW-BACKGROUND ELECTRONICS

Ultra-sensitive experiments, such as experiments investigating neutrinoless double beta decay, require readout electronics with extremely low radiation background so that the detectors are not overwhelmed by noise signals originating in the readout electronics themselves. Berkeley Lab is leading the migration of the LEGEND experiment to integrated low-background electronics.



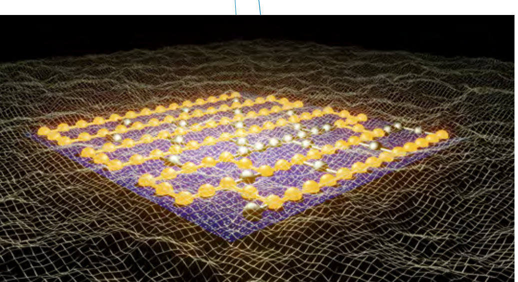
Analog front end, with low mass and low natural radiation background, for germanium detector readout for the LEGEND experiment. The circuit operates at 77 K and provides significantly improved resolution compared with previous solutions. *Credit: Michael Willers, Berkeley Lab*



Stack of high-purity germanium detectors immersed in liquid argon and instrumented with Berkeley Lab-designed analog front ends. *Credit: Michael Willers, Berkeley Lab*

FIVE-YEAR GOALS

- Develop and implement on quantum hardware a simulation of non-perturbative quantum chromodynamics (QCD) dynamics in two spatial dimensions.
- Develop quasiparticle counting sensors and readout technology enabling particle interaction detectors in the ueV to eV regime, such as that needed for future low-mass dark matter searches.



Circuit layout used for the preparation of the ground state of the Schwinger model using 100 qubits on IBM's Eagle-processor quantum computer IBM_CUSCO. *Image Credit: Marc Illa Subina, University of Washington*

7.3 QUANTUM INFORMATION SCIENCE

QIS is a rapidly emerging field with high impact applications in quantum computing, simulations, sensing, and networking.

7.3.1 QUANTUM COMPUTING

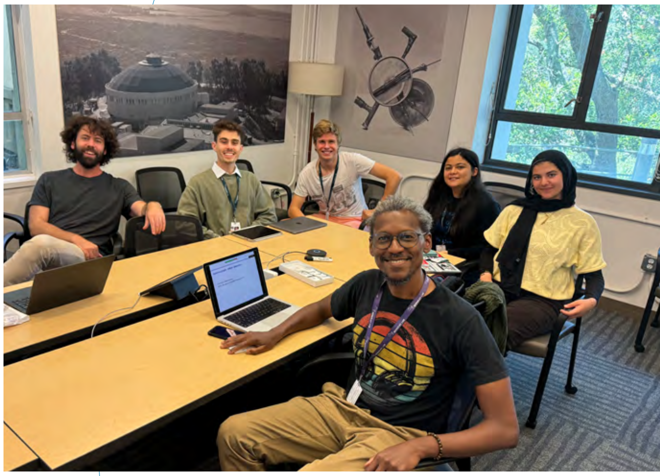
The recently established quantum computing research group provides new avenues for synergistic research with the Applied Mathematics and Computing Research Division to develop theoretical techniques that can simulate the dynamics of field theories in high-energy physics, participating in the concerted national effort to develop quantum computers and open new scientific directions. Just as a quantum computer with a significant number of qubits cannot be simulated by even the most powerful supercomputers, many particle-entangled states in particle physics cannot be calculated with classical computers. Our effort focuses on performing particle physics calculations on quantum computers, once they are mature enough to solve the real-world systems of interest. Both quantum field theory development and quantum computer algorithm development are needed to reach that point, in addition to a quantum-computing-trained theory workforce. Our research has yielded new formulations of quantum field theories, new quantum algorithms and new techniques for noise mitigation, which is a necessity on current quantum hardware. Over the next five years, the goal is to enable simulations of the strong interaction, responsible for binding quarks and gluons into hadrons, and which is not tractable on classical computers in two dimensions. This will lay the foundation for the larger-scale simulations that will open new avenues in High Energy Physics.

7.3.2 QUANTUM SENSORS

The concerted national effort to develop quantum computers and networks has had a significant influence on the Physical Sciences Area detector R&D programs. A QIS ecosystem is emerging, not unlike the early days of digital computing. Since 2018 we have been participating in this development with a Berkeley Lab-led consortium of three Berkeley Lab divisions, five universities, DOE's Oak Ridge National Laboratory, and NASA's Jet Propulsion Laboratory, with the goal of developing improved sensors for very low-energy impulse signals, needed to search for low-mass particle dark matter and rare processes. This includes cryogenic microcalorimeter and quasiparticle counting detectors, optomechanical sensors, and quantum measurement theory.

The quantum sensors program is multidisciplinary at its core, because the nature of very low-energy dark matter and other new physics interactions demands it. With very little available energy, such interactions cannot ionize materials or even excite carriers across semiconductor bandgaps. The only signal channels available are coherent thermal or mechanical modes. This falls in the intersection of particle physics phenomenology and experiment, materials science theory, and quantum measurement. We work closely with the Molecular Foundry, Materials Science Division, and university partners to discover, both theoretically and experimentally, new ways to probe new physics interactions. We work closely with the University of California, Berkeley (UC Berkeley), industry, and the Jet Propulsion Laboratory on superconducting phonon sensors, which share technology with superconducting qubits; with the the Accelerator Technology & Applied Physics (ATAP) Division, the University of Massachusetts Amherst, and Princeton University on single atom and vacancy defect sensors; and with Oak Ridge National Laboratory and Yale University on optomechanical impulse sensors.

Within this program we have achieved the lowest energy threshold, large area (3" diameter) microcalorimeters using transition-edge sensors (TESs). At the same time, we have made strides to understand and mitigate low-energy intrinsic backgrounds in solid materials due to relaxation processes, which were previously hidden by the instrumental noise of less sensitive microcalorimeters. We have advanced understanding of signal propagation in crystal targets and brought the technique of superfluid helium quantum evaporation to maturity levels needed for the initial stages of the TESSERACT program. Questions raised by the work on signal propagation in crystals have informed a phonon engineering program within the new PhononNext Center at Berkeley Lab. We have worked with UC Berkeley on the next generation of the world's more precise fine structure constant measurement using atom interferometry and have developed the measurement theory and launched a new tabletop gravity entanglement measurement using this technology. We have launched the Quantum Invisible Particle Sensor (QuIPS) experiment, together with Yale University, using quantum limited optomechanical measurement to search for sterile neutrino signatures in beta decays.



Quantum physicist Dan Carney (left) with visiting summer students discussing quantum measurement theory and experiments. *Credit: Elizabeth Worthy, Berkeley Lab*

Our quantum sensors program has an exciting path forward. Besides bringing the above developments to fruition, we are developing a next generation of microcalorimeter sensors, both TES and Kinetic Inductance Device based, using hafnium superconductors. We are developing quantum sensors for pixelated, single atom quantum evaporation detection, based on spin qubits on He films and separately on large format superconducting nanowire single photon detectors. We will apply optomechanical sensors beyond the quantum limit. And we will capitalize on quantum materials development to find more sensitive target materials as well as new phonon control and detection schemes.

Connected to Sensing is a portfolio of quantum technology activities in ATAP's Berkeley Accelerator, Controls, Instrumentation (BACI) and Fusion Science and Ion Beam Technology (FS&IBT) Program. This includes classical control of quantum devices at ultrahigh throughput, FPGA electronics for qubit control and readout (in collaboration with the Quantum Systems Accelerator Center), and quantum storage and visualization. Using ion beam technologies, we are creating novel color centers with implantation techniques. These are applied to quantum computing and communication as well as remote sensing of electromagnetic fields.

7.4 LIGHT SOURCE FACILITIES

The Engineering and ATAP Divisions collaborate with partners across Berkeley Lab, leveraging their expertise in accelerator technology, instrumentation, and engineering to provide state-of-the-art facilities that empower scientific discovery.

FIVE-YEAR GOALS

- Upgrade the Advanced Light Source (ALS) injector chain to increase performance and reliability and continue to serve ALS-U.
- Develop novel undulator designs to improve ALS performance and enable ALS-U potential.

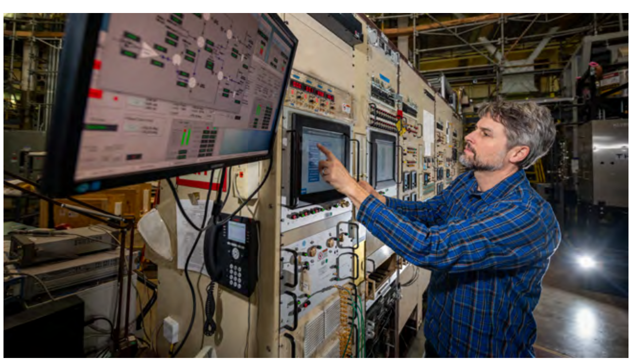
TEN-YEAR GOALS

- Support the ALS-U project in completing and commissioning beam systems and operating the new source to support users.
- Upgrade instrumentation and diagnostic systems to provide state-of-the-art controls and diagnostics capabilities to the ALS and ALS-U.

7.4.1 ADVANCED LIGHT SOURCE ACCELERATOR PROGRAM

ATAP scientists Fernando Sannibale, Marco Venturini, and Simon Leemann inspect the ALS RF section.
Credit: Thor Swift, Berkeley Lab

The ALS has led the world in soft X-ray capabilities for 30 years, serving the core of the Department of Energy's Office of Science's Basic Energy Sciences Program (DOE-BES) mission in this range of photon energies. The ALS is a specialized particle accelerator that generates bright beams of X-ray light for scientific research. Electron bunches travel at nearly the speed of light in a circular path, emitting light from infrared to X-ray in the process. The light is directed through about 40 beamlines to numerous experimental end stations, where scientists from around the world (users) can conduct research in a wide variety of fields, including materials science, biology, chemistry, physics, and the environmental sciences. ALS operation is funded by DOE-BES.



Tom Scarvie, group leader for ALS Accelerator and Floor Operations in ATAP's Advanced Light Source Accelerator Physics Program, restarts an ALS subsystem to initiate users' operation.
Credit: Thor Swift, Berkeley Lab

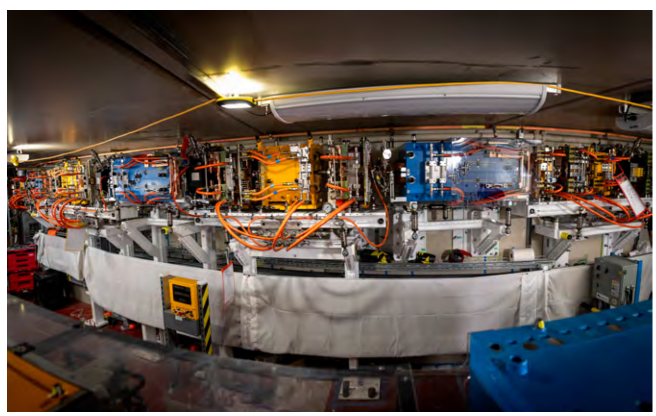
Both the Engineering and ATAP Divisions are instrumental in operating and improving the ALS. An innovative ATAP Division program of accelerator physics and operations drives machine performance, improvements, and upgrades. These upgrades have enabled ever better performance and reliability, maintaining the support of almost 1,000 publications per year. The Engineering Division's staff are integrated into the facility's operations and responsible for developing and improving systems and technology to enhance the facility's performance.

7.4.2 ALS-U: UPGRADING THE ALS TO A FOURTH-GENERATION SYNCHROTRON LIGHT SOURCE WITH ORDERS OF MAGNITUDE HIGHER PHOTON BRIGHTNESS

ALS-U, the major ALS upgrade, is implementing an ultrahigh brightness multibend achromat storage ring replacing the existing ALS ring. ALS-U will provide diffraction-limited beams in the soft X-ray region with fully coherent flux and orders of magnitude higher brightness. These capabilities will enable many experiments that are currently impossible and dramatically improve accuracy and resolution of present ones.

The ALS-U upgrade, initially conceived within the ATAP Division's ALS Accelerator Physics Program, is now also supported by several ATAP Division accelerator programs collaborating on building and commissioning this major DOE user facility with state-of-the-art accelerator design and systems that will pave the road for forefront discovery science for decades to come. The ATAP Division and Engineering Division provide major contributions for all technical areas and stages of the project, including technical management (technical systems lead and control account managers), planning, design, engineering analysis, CAD (computer-aided design) tools, fabrication, technical procurement support, metrology, quality control, integration, assembly, installation, and testing as well as the full range of Engineering Division fabrication capabilities. Engineering disciplinary departments and ATAP Division leaders provide expertise in the technical management and leadership of the ALS-U project.

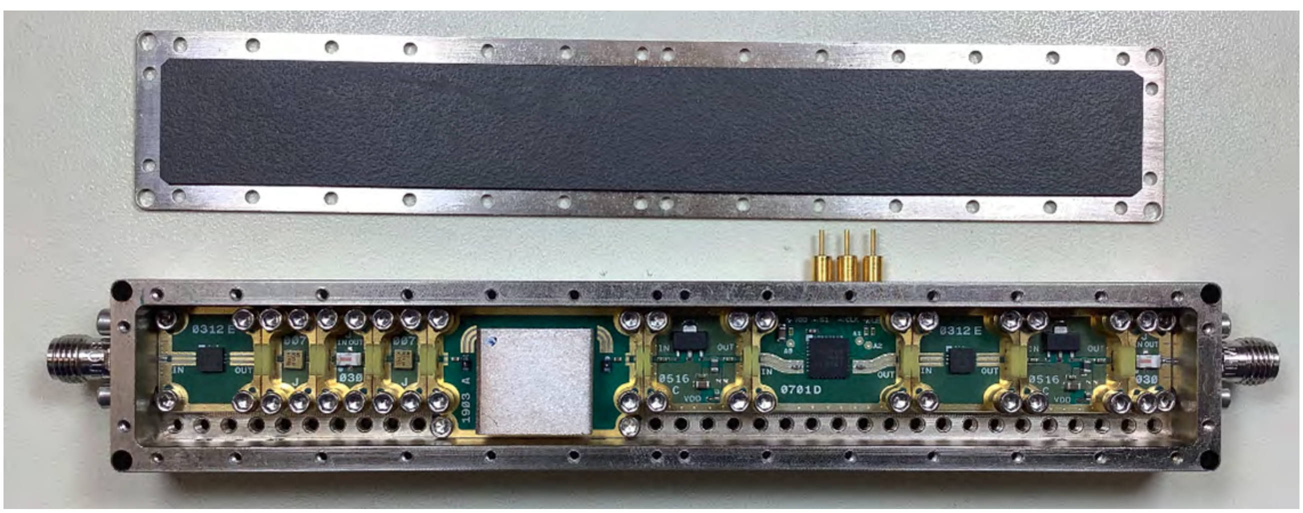
The Engineering Division supports the ALS-U project through the design, fabrication, procurement, and qualification of more than 700 accelerator magnets comprising the accumulator ring, transfer lines, and storage ring. In collaboration with accelerator physicists, our magnet, mechanical, and electrical engineers capitalize on state-of-the-art small-bore vacuum technology to design electromagnets and permanent magnet systems, enabling the performance of low emittance ring lattices and yielding beyond state-of-the-art synchrotron brightness.



Top: Marco Venturini, an ATAP Division senior scientist, with a new ALS-U accumulator ring bending magnet.
Bottom: First accumulator ring sector installed in the ALS tunnel.
Credit: Thor Swift, Berkeley Lab

Various magnet families provide electron beam steering, focusing, chromaticity correction, and bending in both accumulator and storage rings to produce enhanced (low emittance) next-generation light source brightness performance. Other tailored electromagnets enable the transfer of the electron beam through the twisted path between accumulator and storage rings. High-field hybrid-permanent magnets provide the sharp electron trajectory bending that results in an expanded photon beam spectrum output to higher energy.

The Electronics, Software, and Instrumentation Engineering (ESIE) Department is making significant contributions to the ALS-U project in several key areas. For example, ESIE software and hardware engineers are developing state-of-the-art control systems for ALS-U, including an integrated safety system based on specialized safety programmable logic controllers (PLCs), equipment protection systems for the beamlines to protect valuable equipment and the accelerator from equipment faults, and a high-speed control system for machine protection and control. One particular technical advance driven by ESIE engineers is a new beam position monitor (BPM) that leverages advances in FPGA technology to deliver unprecedented beam stability. Most of the BPM system's functionality has been migrated to the digital domain, which interfaces with the beam monitors using a compact custom analog front-end module.



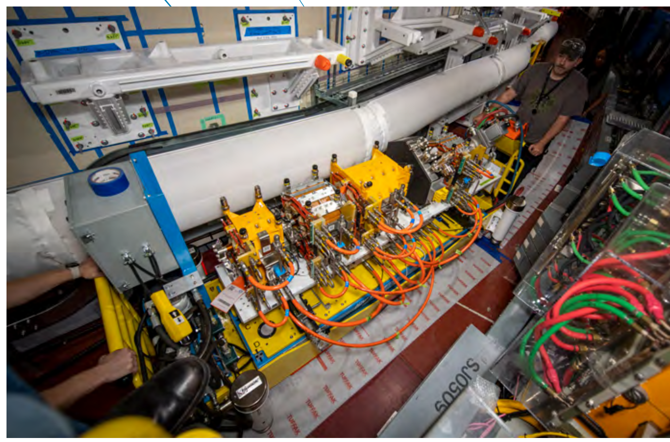
Custom analog front-end module for a BPM. The BPM allows high-precision accelerator control. *Credit: Michael Chin, Berkeley Lab*

Our Manufacturing Engineering & CAD Department engineers are integral to the technical subsystems' teams — such as the magnet, vacuum, pre-staging, and logistics teams — and provide assembly and manufacturing oversight as well as the planning for all installation activities, inventory management, and transport logistics.

The Project Controls Engineering Department contributes to the ALS-U upgrade project through a team of dedicated staff to support the continued development and implementation of a project management controls system aligned with Berkeley Lab's certified earned value management system (EVMS).

As described in Section 6.3.5, the CAD group has developed customized tools in the Windchill Product Lifetime Management (PLM) tool and other databases to integrate model management, fabrication, procurement, and quality assurance.

Technical quality assurance is a key component for large DOE projects. The department has developed a fully integrated database that organically connects



Customized installation tooling developed for the space-restricted installation conditions in the ALS-U tunnel. *Credit: Thor Swift, Berkeley Lab*

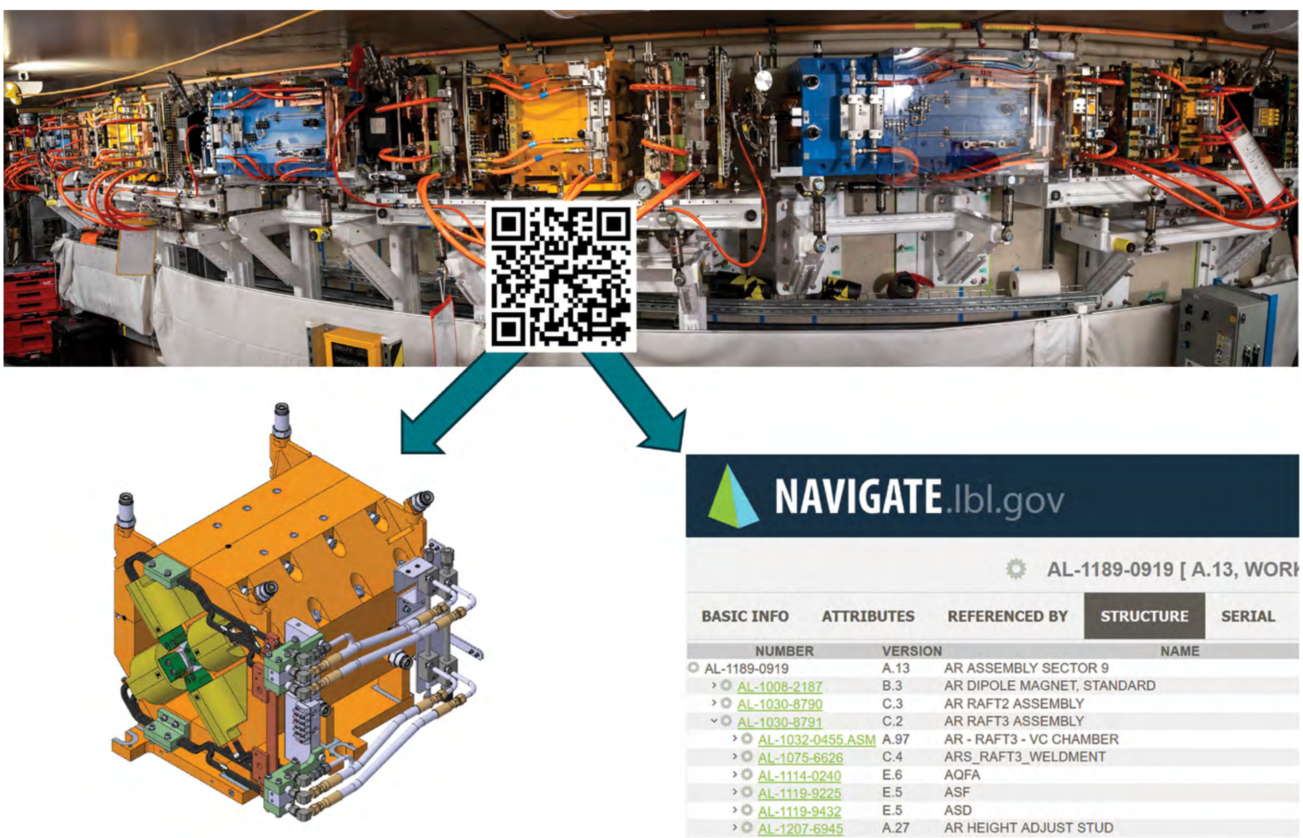
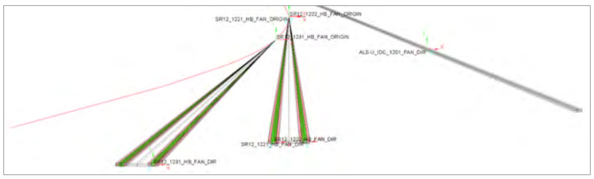


Illustration of how hardware in the field connects with the Windchill configuration management database via a QR code system. Scanning the QR code on an item with any mobile device connects to the central database and shows the information available for that item. *Credit: Daniela Leitner, Berkeley Lab*



James Osborn, a senior researcher in the Engineering Division, works on the integrated ALS-U model and the photon source points, shown in the illustration below the photo. *Credit for photo: Daniela Leitner, Berkeley Lab, Credit for illustration: James Osborn, Manufacturing Engineering & CAD Department*

design data, manufacturing, and quality assurance data, as well as measurement and calibration data. The ALS-U's multidisciplinary challenges require the whole spectrum of the area's expertise and are a strong example of a team science effort.

7.4.3 MAGNETS FOR LIGHT SOURCES

A collaboration among the ATAP and Engineering Divisions with strong ALS connections, the Berkeley Center for Magnet Technology (BCMT) leverages expertise in accelerator physics and vacuum technology to advance undulator systems for synchrotron and free-electron laser (FEL) light sources, as one of its topics. This collaboration (one of BCMT's many activities) focuses on developing permanent magnet hybrid and superconducting undulators, which capitalize on the smaller vacuum bores of modern light sources to expand polarization mode capabilities and extend spectral range.

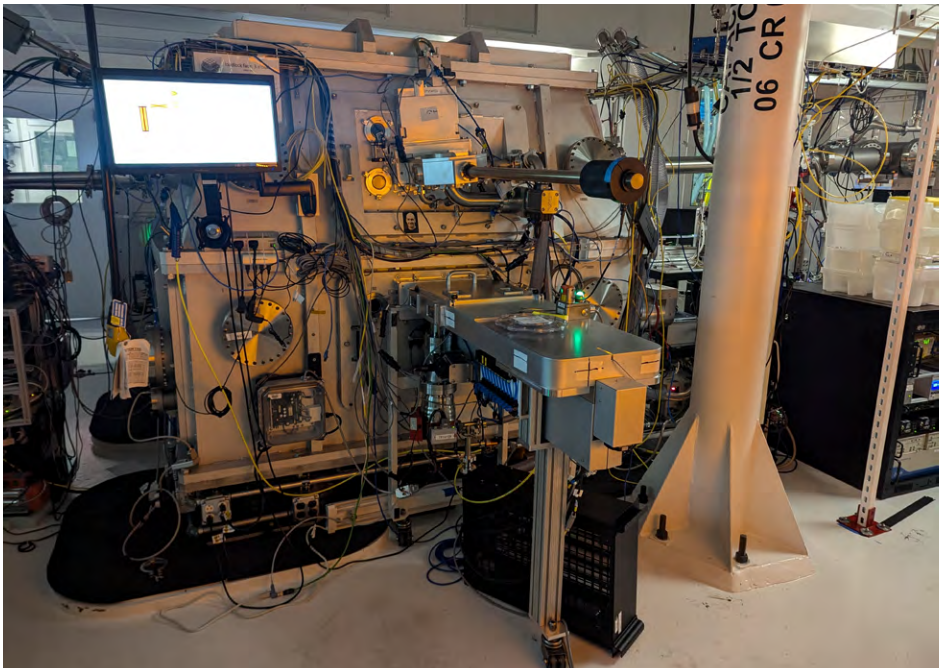
Magnetic arrays on the LCLS-II-HE soft X-ray undulators generate a precise periodic magnetic field that interacts with the electron beam for x-ray production in the LCLS facility.
Credit: Philip Mallon, Berkeley Lab

Key R&D areas include novel tunability mechanisms for permanent/hybrid magnet undulators, Nb_3Sn superconducting undulators for FELs, superconducting helical-bifilar technology, and ultra-compact tunable magnets. These advancements will drive innovation in light source capabilities, paving the way for greener, more affordable, and more compact solutions for scientific discovery and high-energy physics applications.

7.4.4 X-RAY OPTICS AND BEAMLINE DESIGN

In collaboration with the Materials Science Division, the Engineering Division provides technical expertise for the Berkeley Lab Center for X-Ray Optics to enhance short wavelength optomechanical systems and resources to advance the semiconductor industry. It supports development of precision instrumentation enabling state-of-the-art X-ray optical coatings and nano-diffractive optics.

In the coming years, this expertise, with the wider optomechanical and ultrahigh vacuum skills present within the Engineering Division, will be vital to the success of ALS as the team develops beamlines and end stations showcasing the performance of the upgraded ALS, next-generation wavefront-preserving X-ray optics, and extreme ultraviolet (EUV) lithography beyond high numerical aperture.



8 nm resolution Micro Exposure Tool and the EUV Lithography facility at the ALS.
Credit: Arnaud Allezy, Berkeley Lab

Berkeley Lab's contributions to the Oakland Unified School District STEM Fair have been organized by Ina Reichel, the ATAP Division's Outreach and Communications Specialist, for over a decade.
Credit: Oakland Unified School District, May 2024

8. STEWARDSHIP, COMMUNICATION, OUTREACH, AND EDUCATION

Berkeley Lab's initiative to promote and support stewardship values is organized around the core values of team science, respect, trust, innovation, and service. The Physical Sciences Area is firmly committed to fostering a welcoming and supportive work culture. As part of our commitment to our stewardship values, we follow best practices in our recruitment and interviewing processes, support the careers of early career staff, and create an inclusive work environment that supports all staff to reach their full potential. In addition, we engage in communication, outreach, and education activities to share the excitement of our research broadly, and encourage more students to pursue careers in science, technology, engineering, and mathematics (STEM) to increase the pool of talent in STEM.

8.1 STEWARDSHIP

Within the Physical Sciences Area, our approach to effective stewardship is aimed at engaging and empowering all individuals with activities and initiatives at the group, division, and area level so that the concepts are embedded deeply within the area. Each division has its own stewardship committee that meets regularly to develop initiatives and activities that are attuned to the division culture and assimilated and built into the fabric of the division. There is also an area-wide Workplace Life Committee with representatives from each division, that advises the Associate Laboratory Director for Physical Sciences on area-wide initiatives to improve the quality of life for all employees. In addition, the division committee chairs and the Workplace Life Committee chair meet regularly with the Associate Laboratory Director for Physical Sciences to share their strategies, ideas, and best practices, and to look for synergies across the area. These activities will be supported and strengthened in the coming years as we continue to internalize the goals of the stewardship initiative and further integrate them into our area-wide culture.

Recently, the Workplace Life Committee, in collaboration with the Associate Laboratory Director for Physical Sciences, drafted a Physical Sciences Area Statement on Work-Life Balance that summarizes and clarifies lab policies to help employees and supervisors navigate this often-challenging aspect of working in a fast-paced and highly competitive research environment. One of the Workplace Life Committee's earlier recommendations was to initiate an area-wide mentoring program to provide every employee who signs up with a mentor to help them navigate the laboratory, address concerns, feel supported and included, and

GOALS

1. Ensure that all employees can achieve a reasonable work-life balance and feel supported in achieving their career goals.
2. Increase active participation in stewardship activities and Employee Resource Groups (ERGs), and reward and recognize those who participate.
3. Improve supervisor training and support for employee career development.
4. Continue to build strong community ties through communication, outreach, and student programs that develop the STEM career pipeline with a particular focus on our local area for STEM enrichment programs.

benefit from advice for professional challenges they may be facing. The Physical Sciences Area Mentoring Program was launched in 2021 and has been very successful, with increasing participation in subsequent years. The Mentoring Program is open to all employees and students, from all four divisions. In 2024, there were over 70 mentor-mentee pairs. All mentors and mentees receive training in how to conduct a successful mentorship relationship, and surveys administered to each cohort indicate a high level of satisfaction with this program.

The Physical Sciences Area, in collaboration with the human resources team, recently initiated a required two-hour Basics of Supervision training course for all supervisors, whether new or existing. The training ensures that all supervisors understand the basics of Berkeley Lab's workplace policies and the importance of providing regular feedback and engaging with employees to develop individual career paths and encourage employee career growth. Survey feedback indicated that this was a very useful course, and the course material will be available as a continuing resource for all supervisors.

Elina Dluger Rios, Special Programs and Volunteer Manager from Berkeley Lab's K-12 STEM Education and Outreach Program, presents an overview of Berkeley Lab to visiting high school students. All four PSA divisions—ATAP, Nuclear Science, Physics, and Engineering—partner with the K-12 office to host educational events for visiting high school students as part of our outreach efforts. *Credit: Robinson Kuntz, Berkeley Lab*

Another avenue to support employees is through Berkeley Lab's ERGs, which provide a forum for employees to network and work together to support their affiliations. The Physical Sciences Area has participated extensively in the Lab's ERGs, with executive sponsorship of the Early Career Resource Group, the Lambda Alliance, and the Women's Support and Empowerment Council (WSEC) and leadership roles in the Veterans and WSEC ERGs. These activities will continue to be supported and recognized in annual performance evaluations and other forms of recognition.

8.2 COMMUNICATION, OUTREACH, AND EDUCATION

The Physical Sciences Area is committed 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.

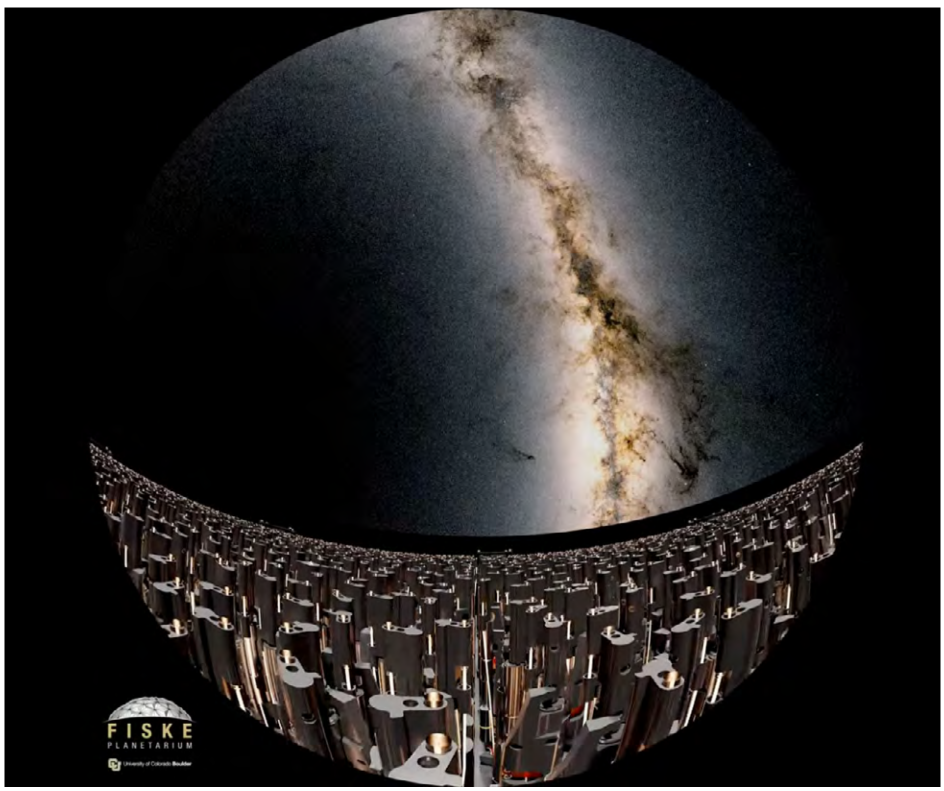
The Engineering Division organizes a Lunchtime Social Hour. *Credit: Hongyan Zhu, Berkeley Lab*

To enhance and extend the impact of each division's communications efforts, we have added an Area Communications Lead who works with Berkeley Lab Strategic Communication on area-related press releases, the area's social media presence, and focused internal communications across all four divisions, including an area newsletter to keep everyone informed and up to date on exciting research developments, individual awards and achievements, and important events. The Accelerator Technology & Applied Physics (ATAP) Division and the Nuclear Science Division have deployed newsletters to their respective internal and external audiences for over 10 years, highlighting scientific accomplishments, employee awards and honors, outreach and education events, and safety spotlights. All four divisions also have a social media presence and utilize those channels to amplify messaging to a demographically diverse audience. We intend to continue and strengthen these communications efforts.

The area's divisions are actively engaged in community outreach and events that invite the broader community to meet our researchers and explore our research. We also provide unique educational opportunities to develop experts for the future of our fields. In the following sections, we describe just a few examples of the exciting programs that we currently offer and that we hope to continue through the coming years:

5000 EYES: MAPPING THE UNIVERSE WITH DESI

The documentary, *5000 Eyes: Mapping the Universe with DESI* (2023), which features recent exciting results from the Dark Energy Spectroscopic Instrument (DESI), was produced by the Fiske Planetarium in Colorado. It was released to planetariums worldwide and had its Bay Area premiere in March 2023. A "flat screen" version of the film is now available to watch for free on YouTube.



DESI's robotic "eyes" in a screenshot from *5000 Eyes: Mapping the Universe with DESI. Credit: Fiske Planetarium*

NUCLEAR SCIENCE DAY FOR SCOUTS

Launched in 2009 by Berkeley Lab's Nuclear Science Division, the annual Nuclear Science Day for Scouts event gives participants an opportunity to learn about nuclear science. The 2023 event featured a tour of the Advanced Light Source (ALS), presentations about different radiation detectors built at Berkeley Lab, and hands-on exercises, including building an electroscope and using a Geiger counter to measure background radiation in everyday objects.

Nuclear Science Day for Scouts, organized by the Nuclear Science Division with volunteers from across the Physical Sciences Area. *Credit: Shannon Kelli, Berkeley Lab*

PHYSICS IN AND THROUGH COSMOLOGY WORKSHOP

The annual Physics in and Through Cosmology Workshop, which was launched in 2006, is offered by the Physics Division to engage high school students and teachers in cutting-edge research in particle physics and cosmology through live presentations and discussions with Berkeley Lab scientists. The June 2023 event was hosted as a virtual two-week workshop for more than 40 students from throughout the Bay Area and around the globe.

COSMOPALOOZA

The Physics Division hosts the annual CosmoPalooza event to showcase the latest updates from large-scale cosmological surveys and collaborations, and the session recordings are presented as open-access video content online. Launched in 2022 in response to the new remote working environment brought on by the COVID-19 pandemic, the October 2023 event engaged a global audience of more than 150 participants each day.

US PARTICLE ACCELERATOR SCHOOL

Particle accelerator science and technology are seldom available through traditional collegiate programs, making specialty schools offering expertly taught courses vital resources. Since 1990, the ATAP Division has taught at the US Particle Accelerator School (USPAS). Engineering and Nuclear Science Division staff have also taught at USPAS. More than 80 people associated with the ATAP Division have taught at USPAS, for more than 100 courses. Many of these courses are team-taught with colleagues from other institutions, building lasting connections throughout the accelerator community. ATAP personnel also teach at the CERN Accelerator School and the Joint Universities Accelerator School (JUAS), and offer short courses in association with the major technical conferences.

Ina Reichel with Alex Kim, a staff scientist in the Physics Division, and Ian Lacey, a principal scientific engineering associate at the ALS, at the Oakland Unified School District STEM Fair, May 2024. *Credit: Oakland Unified School District, May 2024*

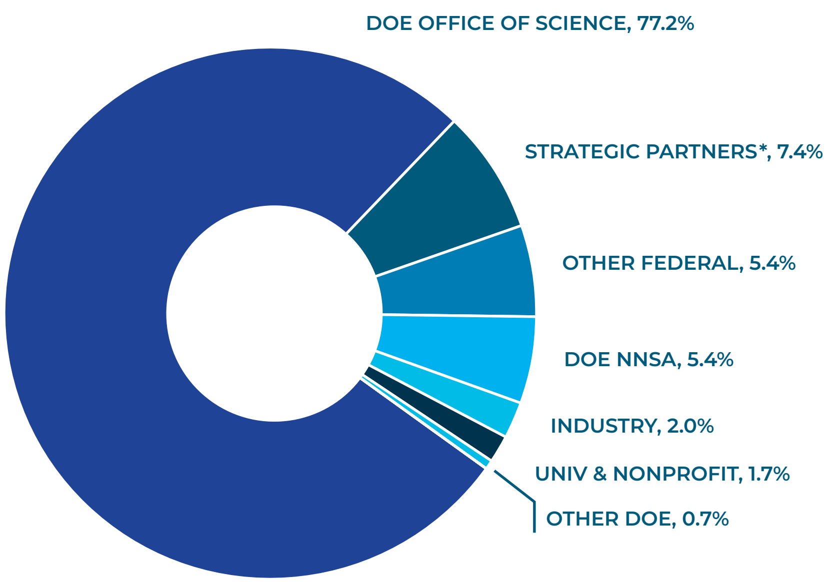
Paolo Ferracin, a senior scientist from the ATAP Division, describes superconducting coils based on niobium-tin superconducting technology for the Large Hadron Collider (LHC) upgrade to Berkeley High School students. *Credit: Carl Williams, Berkeley Lab*

K–12 STEM OUTREACH

K–12 outreach builds a foundation for STEM and supports our stewardship goals by creating a talent pipeline in our local communities. Service to Bay Area public schools is a longtime Berkeley Lab area of emphasis in which the Physical Sciences Area is well represented. Area staff actively participate in outreach programs that focus on STEM aimed at high school students and teachers, and support other programs organized by the Workforce Development & Education office and K–12 Office at Berkeley Lab. For example, ATAP Division researchers regularly teach advanced-placement physics at Bay Area high schools. Physical Sciences Area staff from the ATAP Division and Physics Division have built relationships with the Oakland Unified School District STEM Fair, the Science Accelerating Girls' Engagement in STEM (SAGE) Camp, and the bilingual Science en Acción program. The Physical Sciences Area's goal is to encourage and increase the number of first-time volunteers across all its divisions in the next few years. Activities include the Physics Division's ATLAS Masterclasses in particle physics data analysis and the Engineering, ATAP, and Nuclear Science Divisions' High School STEM Day activities.

9. PHYSICAL SCIENCES AREA AT-A-GLANCE

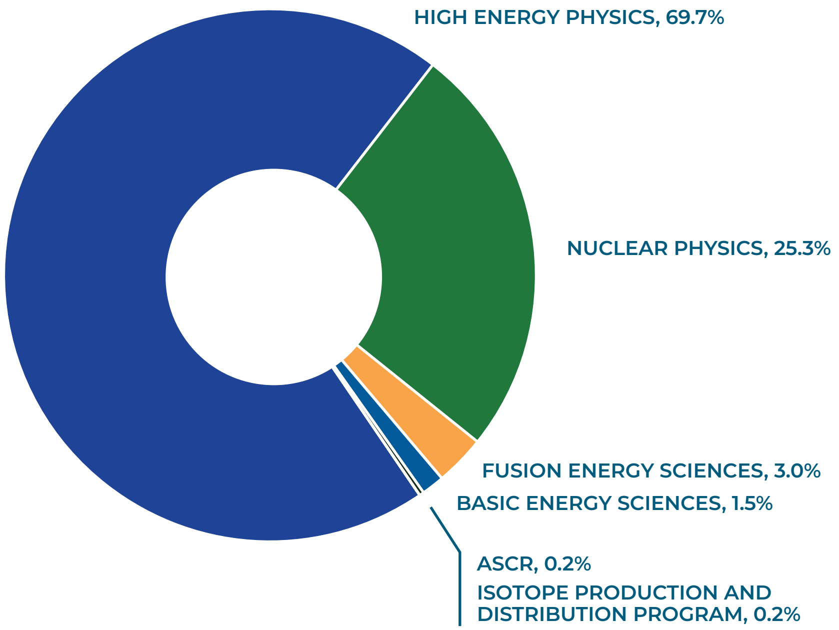
RESEARCH FUNDING SPONSORS
AVERAGE SINCE 2019



* "Strategic Partners" refers to Office of Science funding that comes through collaborations with other DOE laboratories.

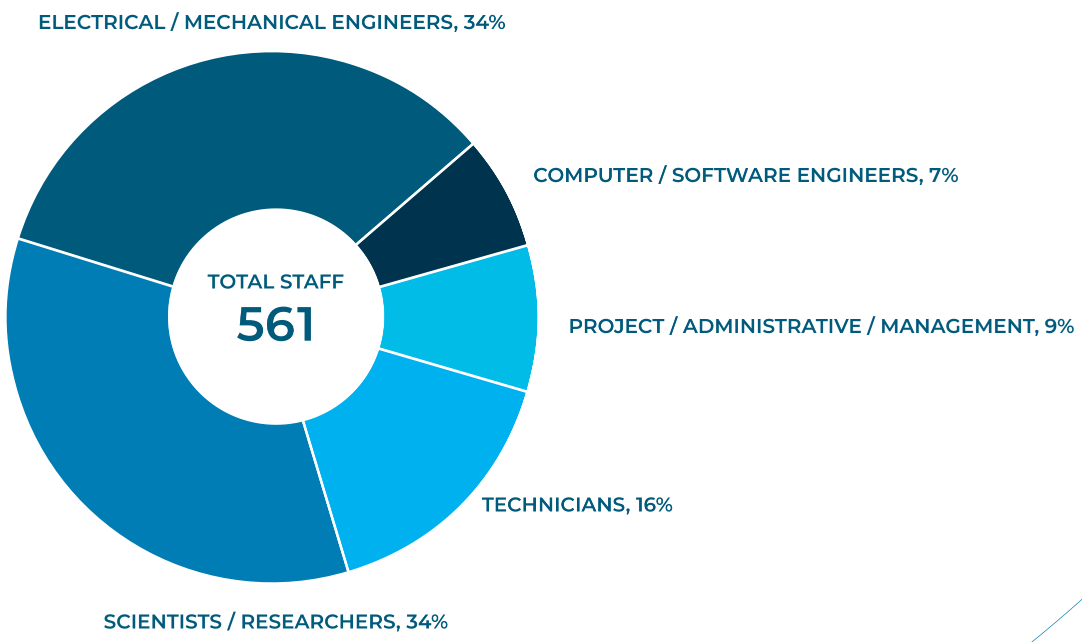
DOE OFFICE OF SCIENCE FUNDING

AVERAGE SINCE 2019

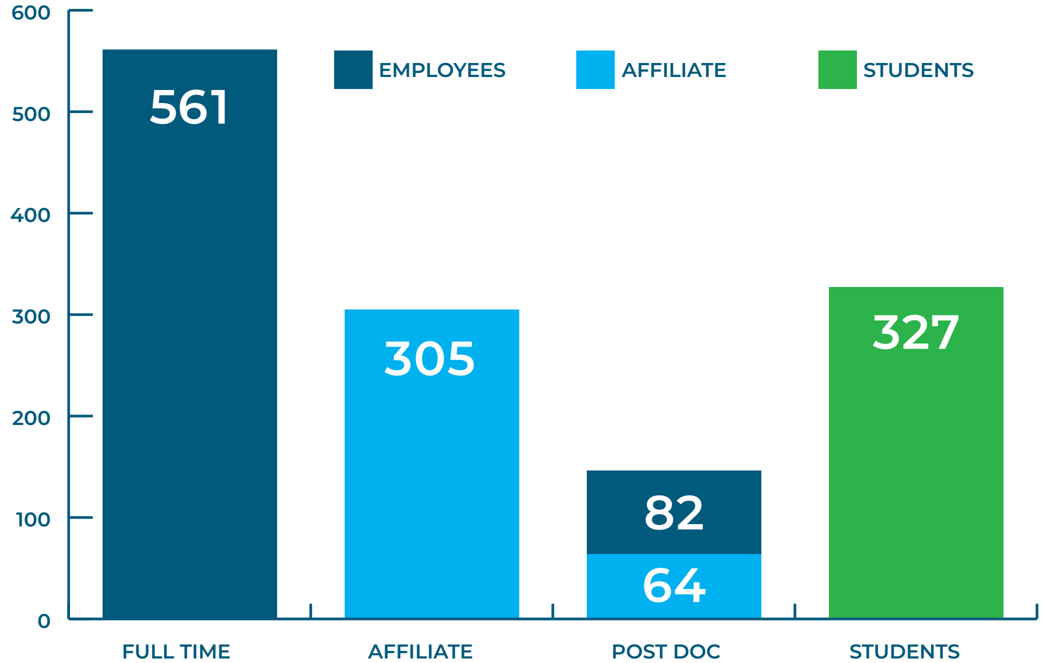


AREA-WIDE FULL-TIME CAREER AND CAREER-TRACK STAFFING

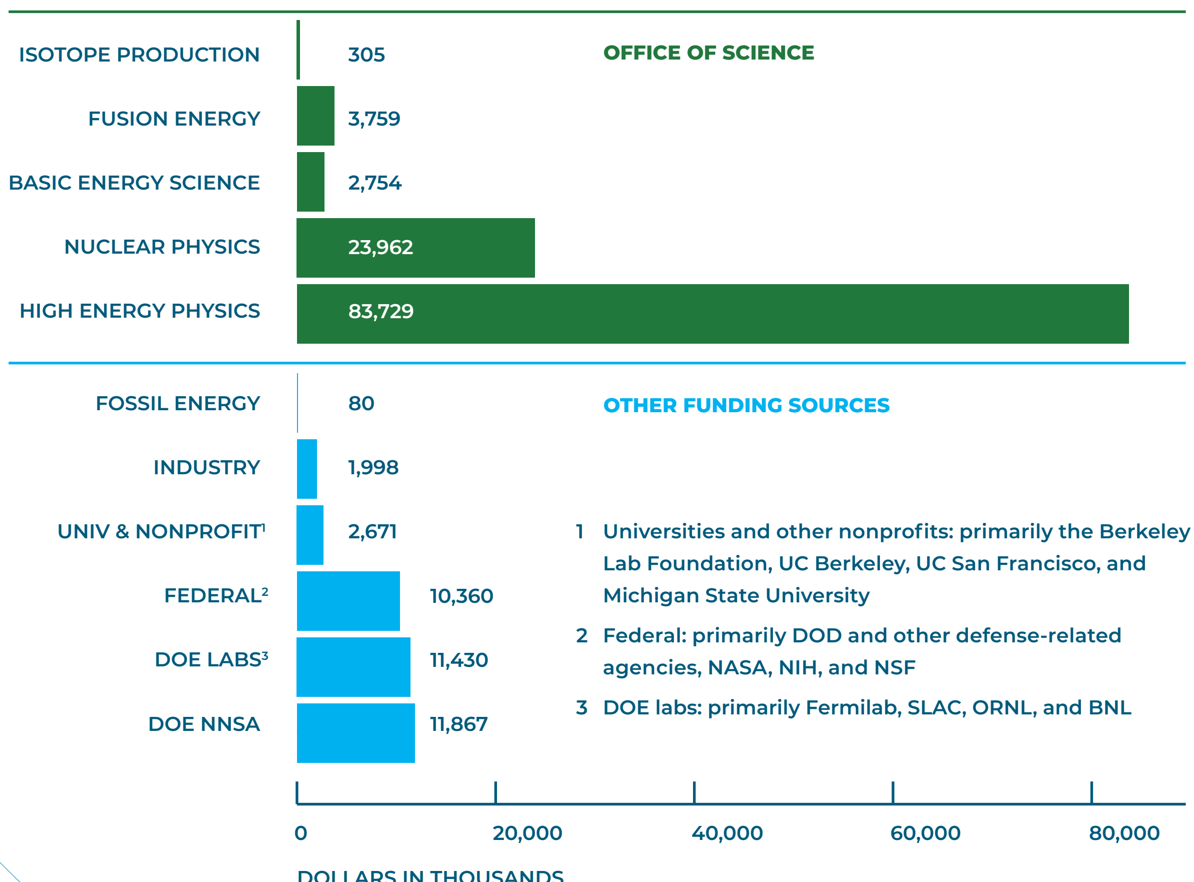
AS OF SEPTEMBER 2024, DISTRIBUTION BY JOB FAMILY



STAFF JOB CLASSIFICATIONS
AS OF SEPTEMBER 2024



FY2024 SPONSOR FUNDING
AS OF SEPTEMBER 2024



1 Universities and other nonprofits: primarily the Berkeley Lab Foundation, UC Berkeley, UC San Francisco, and Michigan State University

2 Federal: primarily DOD and other defense-related agencies, NASA, NIH, and NSF

3 DOE labs: primarily Fermilab, SLAC, ORNL, and BNL

GLOBAL PARTNERS IN ACCELERATOR, HIGH-ENERGY AND NUCLEAR PHYSICS RESEARCH

This list highlights Berkeley Lab's most significant national and international partnerships—including hundreds of research and government organizations as well as universities and campuses worldwide, too numerous to name individually—that play a key role in advancing the Office of Science's research priorities in accelerator, high-energy, and nuclear physics.

- ● Facilities & Experimental Sites
- B University of California, Berkeley
- ◉ Office of Science Partners
- ● International Partners
- ○ Other US Government Partner Labs

NORTH & SOUTH AMERICA

- ☆ DOE Office of Science
- ○ Argonne National Laboratory
- ○ Brookhaven National Laboratory
- ● Dark Energy Spectroscopic Instrument (DESI) at Kitt Peak National Observatory
- ● Facility for Rare Isotope Beams (FRIB) at Michigan State University
- ○ Fermilab
- ● Lawrence Berkeley National Laboratory
- ● Lawrence Livermore National Laboratory
- ● Los Alamos National Laboratory
- ● LUX-ZEPLIN (LZ) Dark Matter Experiment at the Sanford Underground Research Facility (SURF)
- ● National High Magnetic Field Laboratory
- ○ Oak Ridge National Laboratory
- ○ Princeton Plasma Physics Laboratory
- ● Simons Observatory (Chile)
- ○ SLAC National Accelerator Laboratory
- ● SNOLAB (Canada)
- ○ Thomas Jefferson National Laboratory
- ● TRIUMF (Canada)
- B University of California, Berkeley

ASIA

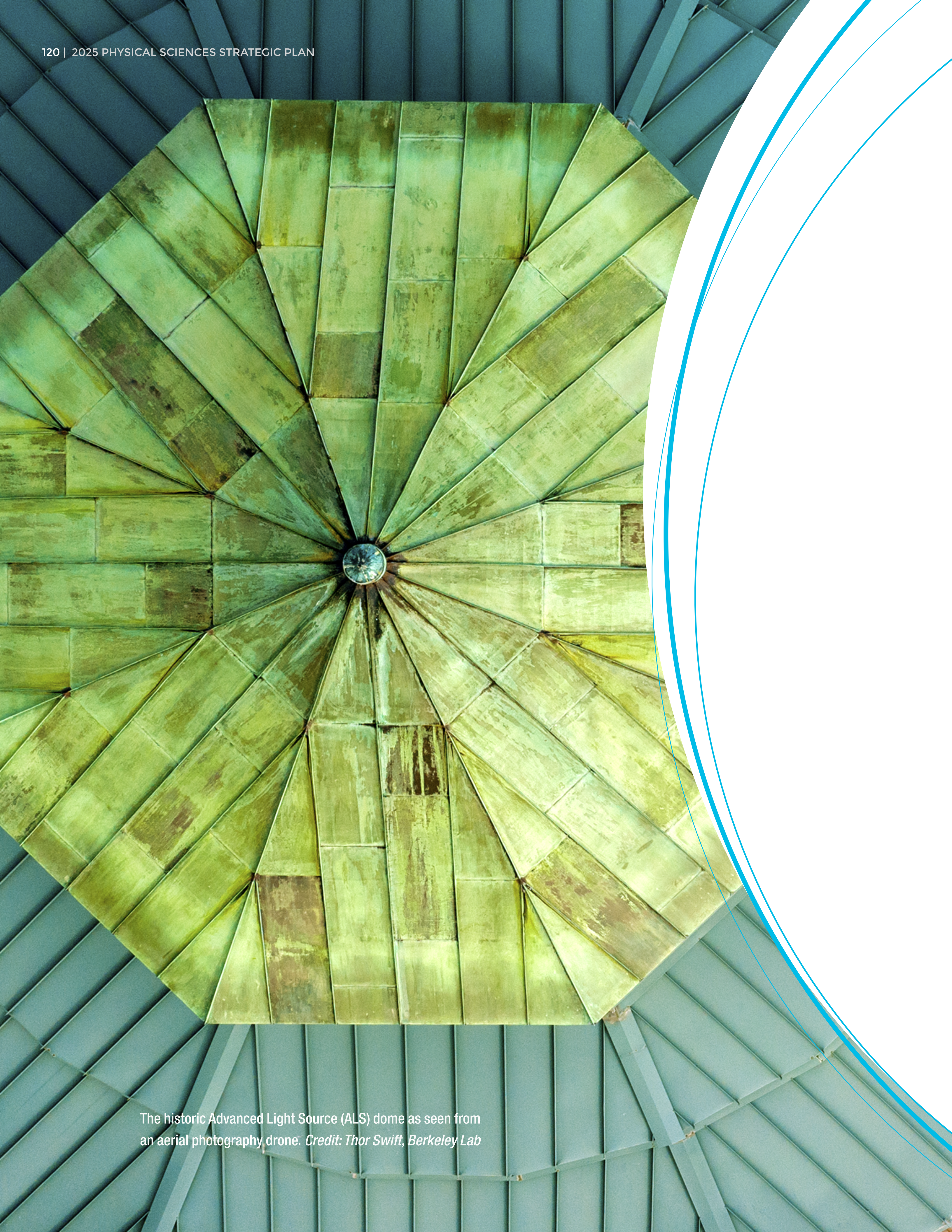
- ● KEK (High Energy Accelerator Research Organization) (Japan)
- ● RIKEN (Institute of Physical and Chemical Research) (Japan)

EUROPE

- ● CEA (Alternative Energies and Atomic Energy Commission) (France)
- ● CERN (European Organization for Nuclear Research) (Switzerland/France)
- ● DESY (German Electron Synchrotron) (Germany)
- ● GSI Helmholtz Center for Heavy Ion Research (Germany)
- ● INFN Gran Sasso National Laboratory (Italy)
- ● LSM (Modane Underground Laboratory) (France)

AFRICA

- ● NRF-iThemba Laboratory for Accelerator-Based Science (South Africa)



The historic Advanced Light Source (ALS) dome as seen from an aerial photography drone. *Credit: Thor Swift, Berkeley Lab*

10. TABLE OF ABBREVIATIONS

AI	artificial intelligence
ALICE	A Large Ion Collider Experiment
ALICE 3	a major upgrade to ALICE
ALS	Advanced Light Source
ALS-U	ALS Upgrade project
AMCRD	Applied Mathematics and Computational Research Division
AMP	Advanced Modeling Program
ANP	Applied Nuclear Physics (ANP) Program, part of the Nuclear Science Division
APEX	Advanced Photon Injector Experiment
AR	augmented reality
ASCR	DOE Office of Advanced Scientific Computing Research
ASIC	application-specific integrated circuits
ASTAE	Advancing Science and Technology through Agile Experiments
ATAP	Accelerator Technology & Applied Physics (ATAP) Division
ATLAS	A Toroidal LHC Apparatus, an experiment at CERN
BACI	ATAP's Berkeley Accelerator Controls and Instrumentation Program
BAND	Bay Area Nuclear Data Group
BAO	Baryon acoustic oscillations
BASE	Berkeley Accelerator Space Effects (BASE) Facility
BCMT	Berkeley Center for Magnet Technology
BELLA	Berkeley Lab Laser Accelerator (BELLA) Center
BIDS	Berkeley Institute of Data Science
BLAST	Beam, Plasma & Accelerator Simulation Toolkit (BLAST) Program
BOSS	Baryon Oscillation Spectroscopic Survey
BPM	beam position monitor
BSM	theories of physics that are beyond the Standard Model
CAD	computer-aided design
CAMPA	Collaboration for Advanced Modeling of Particle Accelerators
CCD	charge-coupled device
CEA	Commissariat à l'Energie Atomique et aux Énergies Alternatives (Alternative Energies and Atomic Energy Commission, France)
CERN	Conseil Européen pour la Recherche Nucléaire (European Organization for Nuclear Research, Switzerland/France)
CLFV	charged lepton flavor violation
CMB	cosmic microwave background

CMM	coordinate measurement machine
CMOS	complementary metal-oxide-semiconductor
CNC	computer numerical control machine
COSI	Compton Spectrometer and Imager
CP	charge parity
CPU	central processing unit
CUORE	Cryogenic Underground Laboratory for Rare Events
CUPID	CUORE Upgrade with Particle IDentification
CW RFQ	Continuous Wave RadioFrequency Quadrupole
CZT	cadmium zinc telluride
DESI	Dark Energy Spectroscopic Instrument
DESY	Deutsches Elektronen-Synchrotron (German Electron Synchrotron, Germany)
DOD	Department of Defense
DOE	Department of Energy
DOE-BES	DOE Office of Science's Basic Energy Sciences Program
DUNE	Deep Underground Neutrino Experiment
eBOSS	Extended Baryon Oscillation Spectroscopic Survey
ECR	electron cyclotron resonance
EESA	Earth and Environmental Sciences Area
EIC	Electron-Ion Collider
ENSDF	Evaluated Nuclear Structure Data File

EoS	equation of state	
Eos	Eos Hybrid Neutrino Detector	
ePIC	Electron-Proton/IonCollider	
EPICS	Experimental Physics and Industrial Control System	
ERG	Employee Resource Groups	
ESIE	Electronics, Software, and Instrumentation Engineering Department, part of Berkeley Lab's Engineering Division	
ESnet	Energy Sciences Network	
EUV	extreme ultraviolet	
eV	electron volt	
	meV	milli-electron volt = 1 thousandth of an electron volt
	keV	kilo-electron volt = 1,000 eV
	MeV	mega-electron volt, or Mega-eV = 1 million eV
	GeV	giga-electron volt = 1 billion eV
	TeV	tera-electron volt = 1 trillion eV
	Sub-eV	sub-electron volts, a threshold neutrino-mass limit
EVMS	earned value management system	
FEL	free-electron laser	

Fermilab	Fermi National Accelerator Laboratory
FES	DOE Office of Fusion Energy Science
FLASH	FLASH radiotherapy, an emerging cancer treatment
FPGA	field-programmable gate array
FRIB	Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU)
FS&IBT	ATAP's Fusion Science and Ion Beam Technology Program
GSI	GSI Helmholtzzentrum für Schwerionenforschung (GSI Helmholtz Centre for Heavy Ion Research, Germany)
GPU	graphical processing units
GRETA	Gamma-Ray Energy Tracking Array
HEDP	high-energy-density physics
HEP	DOE Office of High Energy Physics
HEPIC	High Energy Physics Integrated Circuit Design Consortium
HiRES	high repetition-rate electron scattering, Berkeley Lab's HiRES ultrafast electron diffraction beamline at the ALS
HL-LHC	High-Luminosity Large Hadron Collider, at CERN
HPC	high-performance computing
HPGe	high-purity germanium
HTS	high-temperature superconducting

IC	integrated circuit
IFE	inertial fusion energy
INFN	Istituto Nazionale di Fisica Nucleare (National Institute for Nuclear Physics, Italy)
ITk	Inner Tracker, part of the ATLAS Experiment at CERN
ITkPix	Inner Tracker pixelated detector chip, for ATLAS
ITS2, ITS3	inner tracker systems 2 and 3, future upgrades of ALICE detector subsystems
JUAS	Joint Universities Accelerator School
KATRIN	Karlsruhe Tritium Neutrino Experiment
KEK	Ko Energy-kasokuki Kenkyukiko (High Energy Accelerator Research Organization, Japan)
KISMET	Kinetic IFE (Inertial Fusion Energy) Simulations at Multiscale with Exascale Technology
LBNF	Long-Baseline Neutrino Facility
LCLS	Linac Coherent Light Source at SLAC
LCLS-II	Linac Coherent Light Source II at SLAC
LCLS-II-HE	LCLS-II High Energy upgrade project
LEGEND	Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay
LHC	Large Hadron Collider
Linac	linear accelerator
LLRF	low-level radio frequency

LPA	laser-plasma accelerator
LSM	Laboratoire Souterrain de Modane (Modane Underground Laboratory, France)
LZ	LUX-ZEPLIN
MAPS	Monolithic Active Pixel Sensors
MARS	Mixed Axial and Radial field System
MKID	Microwave Kinetic Inductance Device
ML	machine learning
mmWave	millimeter waves
MSI	minority-serving institutions
MSU	Michigan State University
Mu2e	Muon-to-Electron Conversion Experiment
MVTX	MAPS-based Vertex Detector
ND-LAr	Liquid Argon Near Detector, part of DUNE
NEG	non-evaporable getter
NERSC	National Energy Research Supercomputing Center
NNDC	National Nuclear Data Center
NNSA	DOE National Nuclear Security Administration
NRF-iThemba	National Research Foundation iThemba Laboratory for Accelerator-Based Science (South Africa)
NSD	Nuclear Science Division
NSAC	Nuclear Science Advisory Committee

PANDA	Platforms and Algorithms for Networked Detection and Analysis
pCM	parton center-of-momentum, or parton center-of-mass, the energy of the elementary particles inside an accelerator as they collide
PDG	Particle Data Group
PET	positron emission tomography
PLCs	programmable logic controllers
PLM	Product Lifetime Management
QA	quality assurance
QCD	quantum chromodynamics
QGP	quark-gluon plasma
QIS	quantum information science
R&D	research and development
RBE	relative biological effectiveness
REBCO	rare earth barium copper oxide
RF	radio frequency
RHIC	Relativistic Heavy Ion Collider
RIKEN	Rikagaku Kenkyusho (Institute of Physical and Chemical Research, Japan)
RNC	Relativistic Nuclear Collisions
RPP	Review of Particle Physics
SciDAC	Scientific Discovery through Advanced Computing Program
SDF	Scene Data Fusion

SDL	Semiconductor Detector Lab
SEL	Scintillator Engineering Lab
SiC LGAD	silicon carbide low gain avalanche diode
SiP	systems-in-a-package
SiPM	silicon photomultiplier
SLAC	SLAC National Accelerator Laboratory, originally the Stanford Linear Accelerator Center
SM	theories corresponding to the Standard Model of particle physics
SMP	Superconducting Magnet Program
SNO	Sudbury Neutrino Observatory
SNO+	SNO+ experiment, successor to SNO
SNOLAB	SNO facility expansion
SOI	silicon-on-insulator
STAR	Solenoidal Tracker
STEM	science, technology, engineering, and mathematics
SURF	Sanford Underground Research Facility
SVT	silicon vertex tracker
TEM	transmission electron microscopy
TES	transition-edge sensor
TPC	time projection chamber
UC	University of California
UED	ultrafast electron diffraction
UHV	ultrahigh vacuum
USNDP	US Nuclear Data Program
VENUS	Versatile ECR ion source for Nuclear Science
VR	virtual reality
WBS	Work Breakdown Structure
WIMP	weakly interacting massive particle
WJO	Web Job Order
XLZD	XLZD Dark Matter Detection Consortium, an international consortium of researchers from the XENON Dark Matter Project, the LZ Dark Matter Experiment, and the DARkmatter WImpsearch with liquid xenoN (DARWIN) Project

Acknowledgements:

The Physical Sciences Area is grateful to the many individuals, across all four divisions, who supported the development of this 10-Year Strategic Plan. Their exemplary work and commitment to excellence has resulted in a forward-looking strategy that will inform and guide our research over many years. A special thank you to those who led the editing, coordination, and production of this document, including our Area Communications Lead, Marsha Fenner, and our Creative Services Office team, Eduardo de Ugarte, Jessica Scully, Thor Swift, Caitlin Youngquist, and Meghan Zodrow.

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25-PSAO-10137