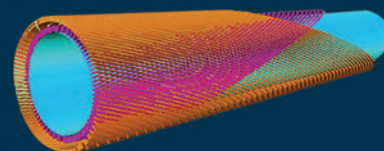
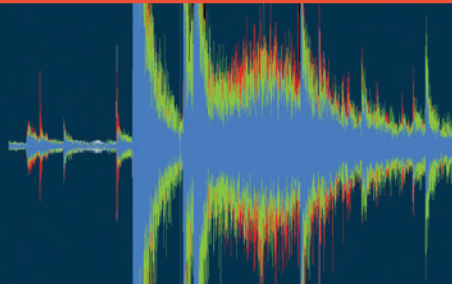
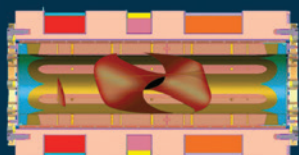
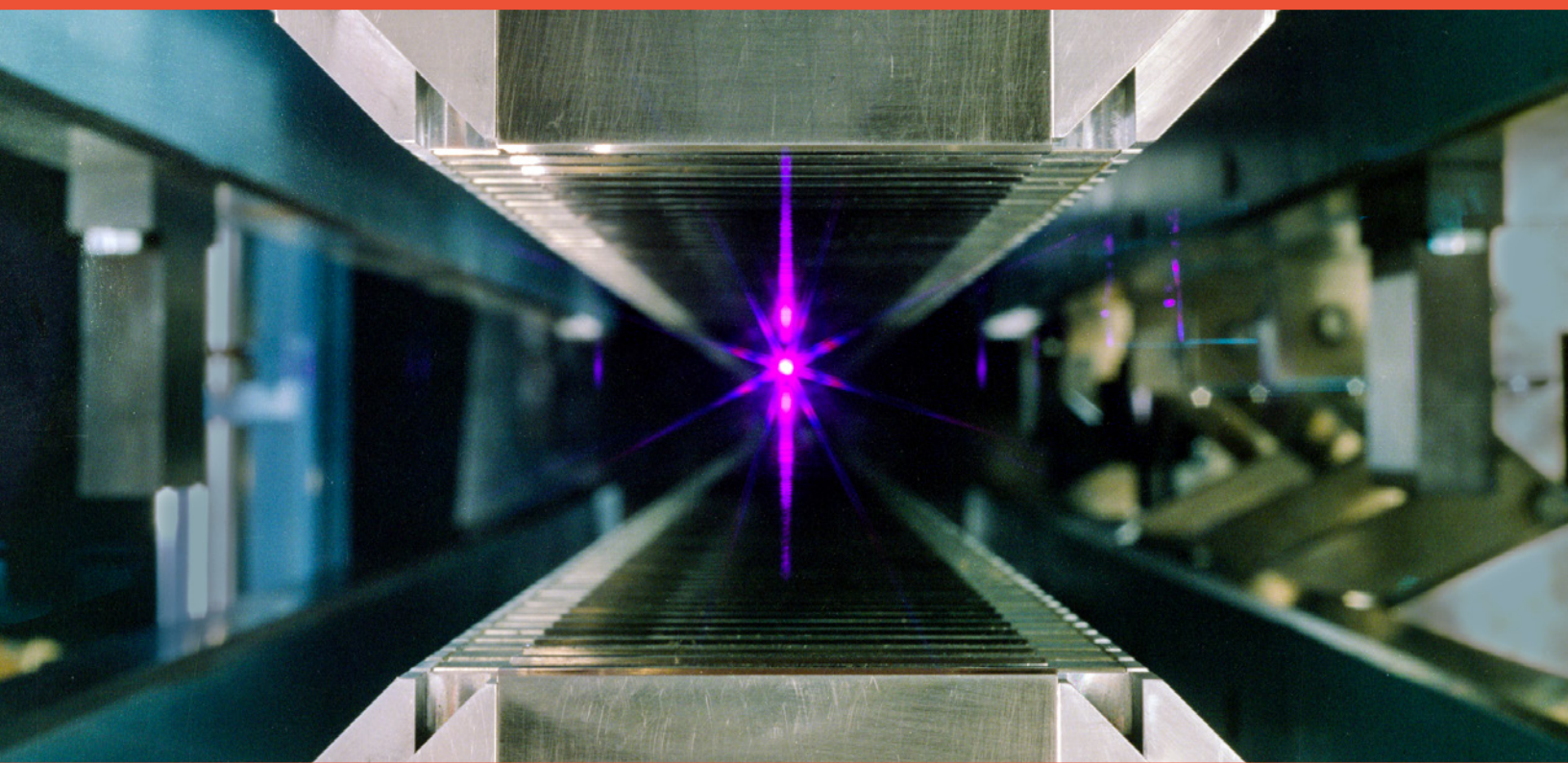
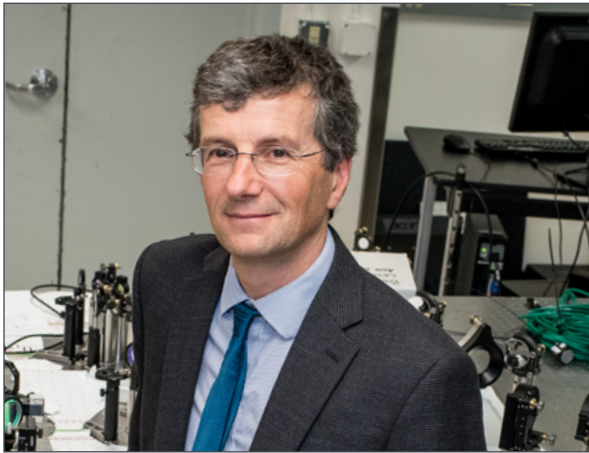


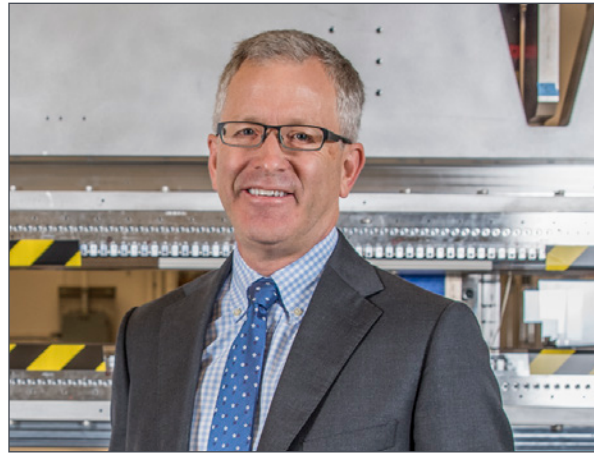
Berkeley Center for Magnet Technology Strategic Framework



Serving the Laboratory and the larger DOE community as a full-spectrum resource for magnet technology



Wim Leemans
Director, Accelerator Technology
& Applied Physics Division



Henrik Von Der Lippe
Director, Engineering Division

The Berkeley Center for Magnet Technology (BCMT) serves LBNL and the larger DOE community as a full-spectrum resource for both R&D and schedule- and cost-driven, project-oriented production of advanced magnet systems.

The BCMT is an interdivisional organization managed jointly by the Accelerator Technology and Applied Physics (ATAP) and the Engineering Divisions of LBNL. It 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.

The BCMT combines an internationally recognized R&D component with LBNL Engineering's core capabilities in magnet design, mechanical integration, fabrication, performance testing, and quality assurance. The combination provides a solid framework to plan and execute research and projects related to magnet technology.

VISION

The Berkeley Center for Magnet Technology will provide leadership in high performance accelerator magnet R&D, magnet system design and manufacturing.

MISSION

Serve as a center of expertise for integrated magnetic systems science and engineering, spanning the entire range from materials science through design, fabrication and implementation of complex magnetic systems, in support of the DOE Office of Science mission.

BCMT STRATEGIC GOALS

GOAL 1:

Be world leaders in accelerator magnet R&D, design, and analysis, for superconducting, normal-conducting and permanent-magnet systems, through the use of advanced modeling techniques and integrated physics models, engineering and testing capabilities.

GOAL 2:

Integrate and leverage our unique resources in design, fabrication and magnet testing capabilities in support of Berkeley Lab's mission and the greater DOE Office of Science.

GOAL 3:

Serve as a catalyst for magnet technology transfer to industry via DOE's Accelerator Stewardship program.

BCMT PROGRAM AREAS AND KEY OBJECTIVES

We will be the partner of choice throughout the DOE complex in these three program areas:

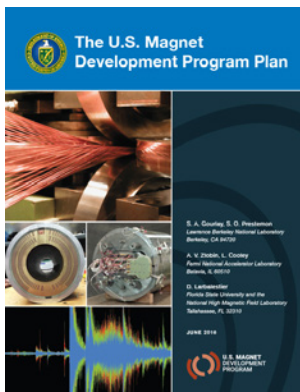
I: MAGNETS FOR LIGHT SOURCES

Develop magnetics systems for synchrotron-light facilities, including storage rings and free-electron lasers (FELs).

Examples include the Advanced Light Source and its proposed upgrade, ALS-U, SLAC's Linac Coherent Light Source-II, the Berkeley Lab Laser Accelerator Center, LCLS-HE, Matter-Radiation Interaction In Extremes (MaRIE) FEL, and beyond. Supporting the ALS-U project to develop a baseline design for the lattice magnets and an initial suite of insertion devices and operational modes is a BCMT priority.

II. SUPERCONDUCTING ACCELERATOR MAGNETS

Drive development of superconducting magnet technologies to enable the next generation of collider facilities.



The Superconducting Magnet Program (SMP) at LBNL, supported by the DOE Office of High Energy Physics (OHEP), has a long history of extending the limits of superconducting magnet technology for accelerators. In recognition of our technical leadership, the OHEP has designated LBNL as the lead laboratory for the multi-institutional U.S. Magnet Development Program (MDP) that will integrate magnet R&D efforts across the United States. Partners of MDP include other national laboratories and university groups engaged in the development of magnet technology and superconducting materials. The same technologies developed under the HEP-funded program can be applied to the future magnet needs of the DOE Office of Nuclear Physics.

III. ADVANCED CONCEPTS AND APPLICATIONS

Provide unique resources and expertise to the DOE Office of Science in the form of superconducting materials and magnets beyond the present capabilities of industry and outside the current program scope.

Examples include next-generation electron cyclotron resonance (ECR) magnet systems, fast-ramping magnets for future electron-ion colliders, novel superconducting magnets for proton and carbon gantries for medical therapy, and magnet R&D for compact fusion devices.



Program Area I: **Magnets for Light Sources**

Ultimate storage-ring and FEL light source performance requires magnets spanning the range from conventional (normal-conducting, iron-core) electromagnets and hybrid magnets (incorporating permanent magnets and magnetic poles), to pure permanent-magnet systems, to superconducting magnets using materials at or beyond the state of the art.

A state-of-the-art undulator and lattice magnet measurement facility is also critical for the magnet characterization and tuning necessary to achieve the full performance potential of today's accelerators. Finally, magnet measurement and tuning technologies beyond the present state of the art, e.g., pulse-wire techniques and small-bore probes, need to be developed to extract full performance potential from small-bore undulators, the premier radiation sources for the FELs and storage-ring light sources being built or envisioned today.

GOALS OF PROGRAM AREA I: MAGNETS FOR LIGHT SOURCES

To make BCMT a comprehensive magnetics technology resource and partner for DOE light source projects, we are pursuing development of:

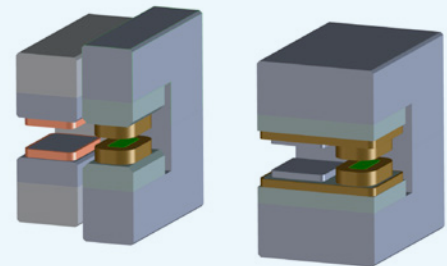
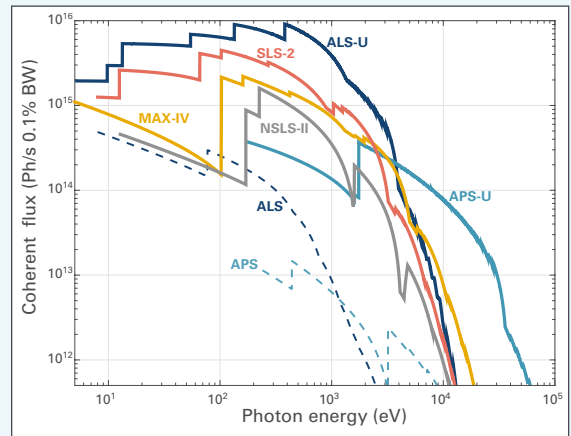
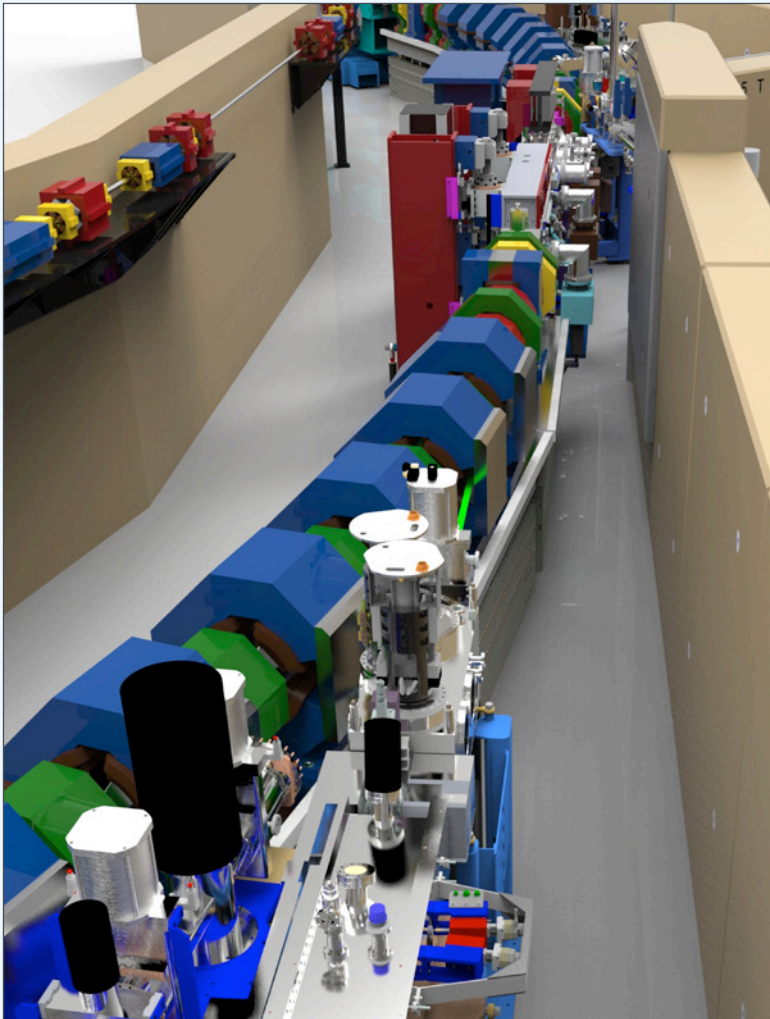
- 1. Compact lattice magnetics capable of realizing the ultimate brightness performance in the Advanced Light Source Upgrade, a diffraction-limited storage ring.**
- 2. High-field and large spectral range capability in small-bore undulators, enabling ultimate linear and variable-polarization radiation performance in diffraction-limited synchrotrons.**
- 3. Design and fabrication of vertically and horizontally polarizing undulators for variable gap free-electron lasers that maintain field quality over an extended magnetic field range, enabling an expanded output radiation spectral range.**
- 4. Magnetics measurement capabilities, enabling low-noise, high-accuracy tuning and characterization of both the lattice magnets that manipulate the particle beam and the undulators that produce the synchrotron light.**

GOAL 1: COMPACT LATTICE MAGNETICS

Lattice magnets must effectively bend, focus, and manipulate individual charged particles within the circumferential space allotted in a synchrotron. This often necessitates combined-function or high-field focusing capabilities, sufficiently free of magnetic errors so as not to lose or degrade the beam. We will support the design, fabrication, measurement, and quality control of an entirely new complement of lattice magnets to achieve the performance potential of state-of-the-art planned and future light sources, such as a diffraction-limited ALS Upgrade.

Superconducting lattice magnets can offer extended photon energy reach to an expanded number of researchers. BCMT aims to develop wavelength-shifting magnets appropriate for the science needs of synchrotron light source users.

Permanent magnet technology offers the possibility of ultimate compactness and highest gradients in state-of-the-art small-bore light sources. BCMT explores the limits of the field strength, compactness, field quality, and tunability of this class of designs, with possible application to accumulator rings, future synchrotrons, and beyond.

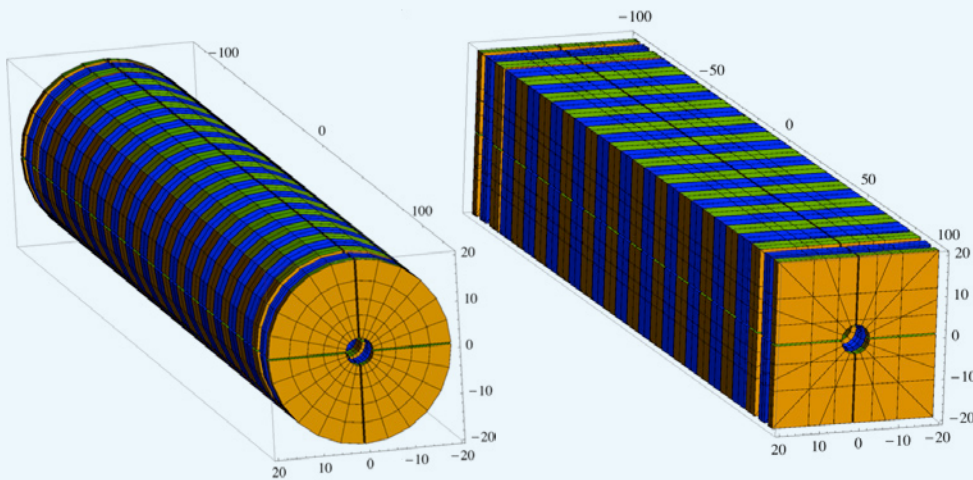


Synchrotron Lattice Magnets

New small-bore vacuum and magnet technologies, coupled with new storage-ring magnetic lattices, will usher in a new generation of diffraction-limited upgrades to the ALS and similar facilities. BCMT is pioneering new designs to realize these possibilities.

GOAL 2: SMALL-BORE UNDULATORS

Undulators with extremely small bores will be able to take optimal advantage of both diffraction-limited emittance lattice designs and state-of-the-art vacuum technology to produce photon brightness beyond what is presently possible. This will open new avenues of imaging and spectroscopy for energy, medical, and chemical sciences. Our goal is to develop these small-bore undulator designs to fully exploit the new companion technologies.



Small-bore undulators for diffraction-limited ultimate performance at ALS-U

Small-bore radiation-producing devices will enable ultimate photon brightness performance over extended spectral ranges for both linear and variably polarizing undulators.



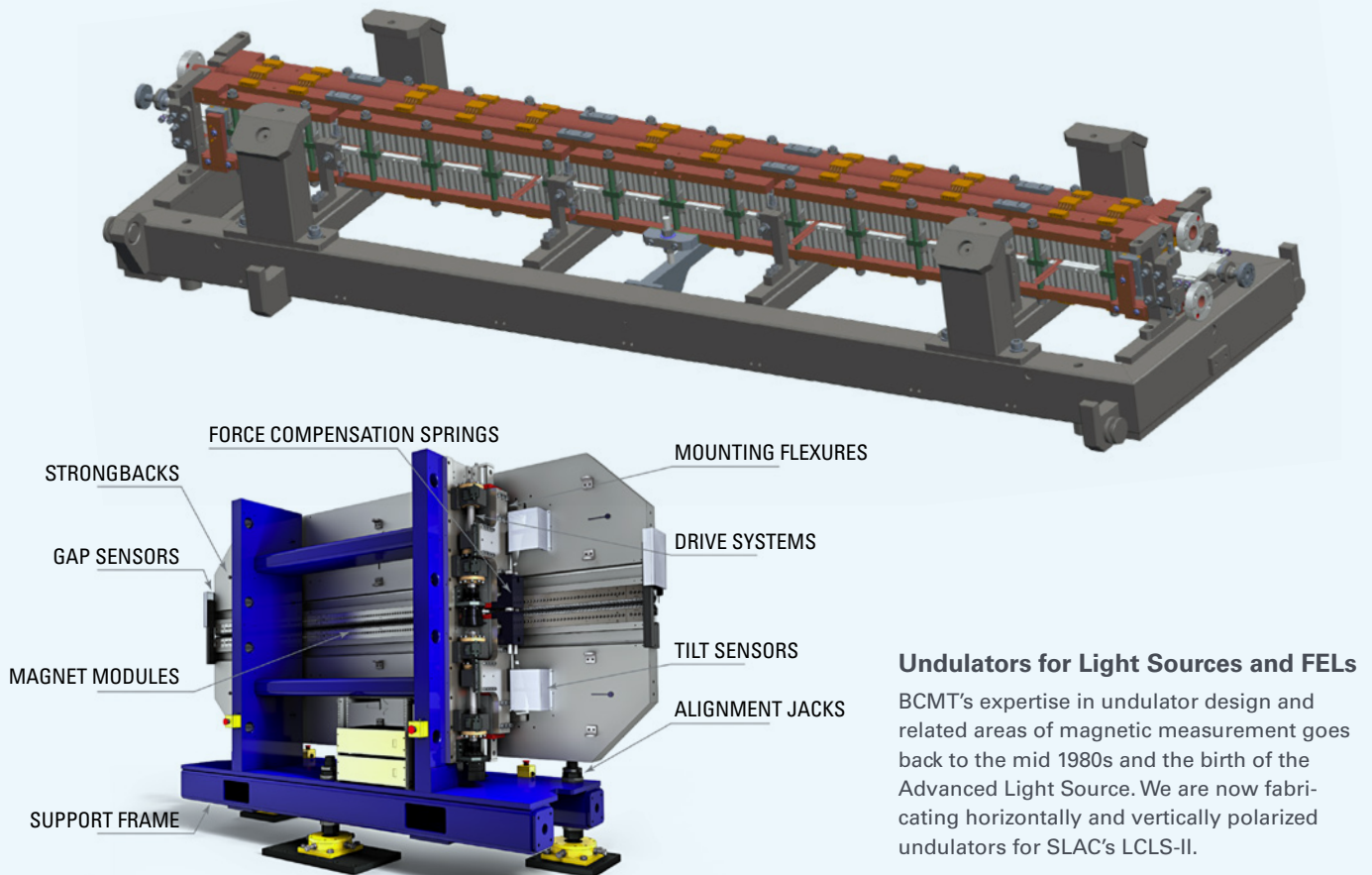
GOAL 3: FEL UNDULATORS

FEL undulators, specifically those that BCMT is designing, fabricating, and tuning for LCLS-II, require extended spectral range capability, which in turn necessitates variable gap magnetic structures in permanent magnet-hybrid designs. BCMT's goal is to develop and fabricate novel magnetic structures that maintain phase-error control (and thus laser/e⁻ beam synchronization) over the entire radiation output spectral range.

Horizontally- and vertically-polarizing devices are being designed, fabricated, tuned, and performance-qualified for LCLS-II's 2019-2020 project completion.

Looking beyond these present-day challenges, BCMT's research on superconducting undulator technology (with Nb₃Sn superconductor, for example) is aimed at expanding and extending performance of future FELs such as LCLS-HE at SLAC and MaRIE at LANL. The objective: providing users with beams that surpass the present state of the art in brightness, photon energy (e.g., for MaRIE, up to 65 keV in the fundamental and ~120 keV and beyond in harmonics), and tunable photon range.

ALS, ALS-U, LCLS-II, BELLA, and beyond will all benefit from the array of magnet measurement and characterization technologies, including novel pulsed-wire and small-bore Hall probe measurement capability.



GOAL 4: MAGNETIC MEASUREMENT

Magnetic characterization and tuning are integral to achieving ultimate performance in lattice magnets and undulators. The BCMT's Magnet Measurement Facility is a temperature-controlled and low-vibration/low-noise environment that enables the precise magnetic measurement and tuning necessary for optimal magnet performance. Our goal is to develop the facility's capabilities to meet the needs of ALS-U, LCLS-II, and beyond.

Key features being incorporated include a new Kugler granite measurement bench, as well as Hall probe, flip-coil, rotating coil, and advanced pulsed-wire measurement capabilities.

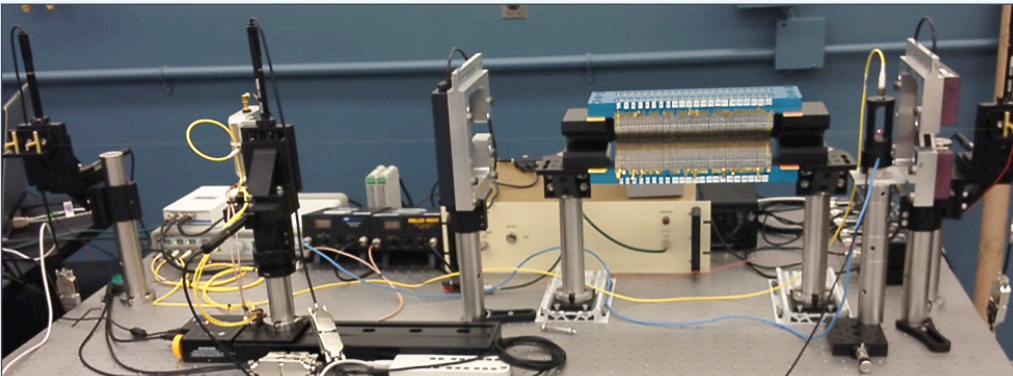
Provisions are being designed and installed for crucial new capabilities:

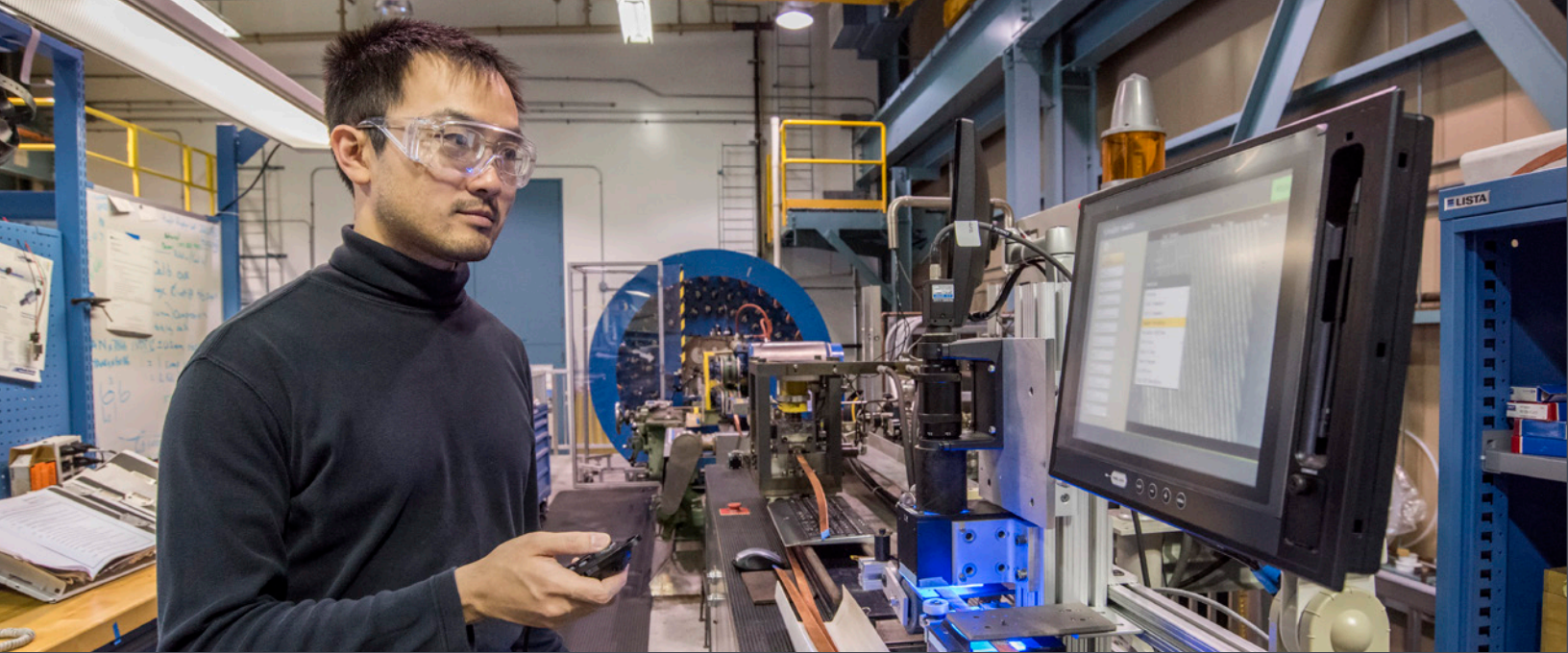
- Rapid side access to lattice magnets (critical for ALS-U) and undulators (critical for LCLS-II, with production undulators being fabricated in 2017-2019) is being implemented.
- Closed small-bore (pulsed-wire and Hall probe) measurement capabilities [critical for ALS-U, perhaps in the 2020 timeframe, and future LCLS-HE and MaRIE FELs] are being designed, fabricated, and installed.
- An automated Helmholtz coil for individual block measurement will round out the measurement suite.



BCMT's Temperature-controlled, Low-noise, Low-vibration Magnet Measurement Facility

ALS, ALS-U, LCLS-II, BELLA, and beyond will all benefit from the array of magnet measurement and characterization technologies, including novel pulsed-wire and small-bore Hall probe measurement capability. Shown here is an LCLS-II prototype soft-x-ray FEL undulator undergoing characterization.





Program Area II: **Superconducting Accelerator Magnets**

Particle colliders for high-energy physics, with their requirement for high magnetic fields, have driven the development of the most advanced superconducting magnets. BCMT traces one of its deepest roots to the early days of this field and is now among its leaders, with an unparalleled integration of design tools and a series of field-strength records in accelerator-style magnets. BCMT's program goals in this arena directly reflect and amplify those put forth by the U.S. Magnet Development Program (MDP), a multi-institutional DOE High Energy Physics (HEP) R&D program led by LBNL.

GOALS OF PROGRAM AREA II, SUPERCONDUCTING ACCELERATOR MAGNETS

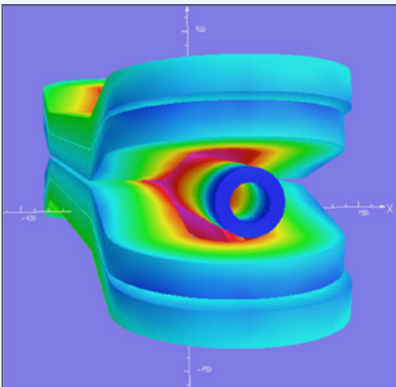
- 1. Lead and execute the U.S. Magnet Development Program in the exploration of high-potential, high-risk, novel superconducting magnet designs, technologies, and materials that, if successful, could revolutionize HEP collider capabilities.**
- 2. Design, develop and fabricate high field magnets as part of the LARP/HiLumi-LHC collaboration to enable ultimate magnet performance capability for the LHC upgrade.**
- 3. Develop novel superconductors and their application to accelerator magnets, including Nb_3Sn and high- T_c superconductors.**

GOAL 1: GAME-CHANGING HEP CAPABILITIES

Novel magnet designs aimed at taking performance to the next level requires willingness to take risks. BCMT's core-program goals are to judiciously choose, then develop, magnet designs with game-changing potential.

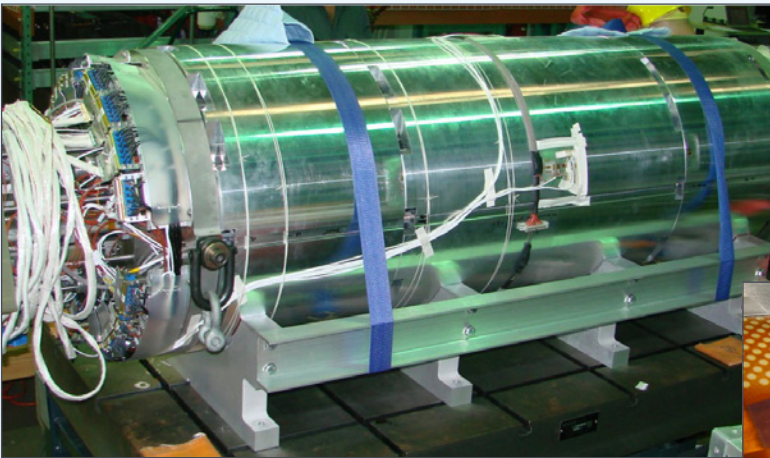
GOAL 2: LARP/HIGH-LUMINOSITY LHC

BCMT aims to ensure reliable, robust high-field superconducting quadrupole magnets for the HiLumi-LHC collaboration. As a key member of LARP, LBNL has contributed important technology that has led to the success of LARP and the initiation of the HiLumi-LHC accelerator upgrade project. LBNL will work closely with lead lab FNAL and our partner lab BNL in producing the U.S. magnet contribution to the LHC upgrade.



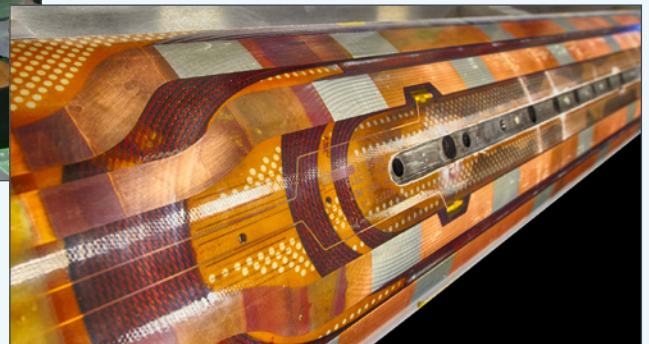
Superconducting Magnet Program: A Common Foundation for Advancement in Many Areas

Besides R&D that is strongly focused on magnets for a particular project, the Superconducting Magnet Program in ATAP Division performs research of long-term general benefit. This is the home of high-risk but high-potential payoff R&D that expands the limits of technology, a high-leverage investment with a wide variety of applications.



LARP: Next Chapter in the LHC Story

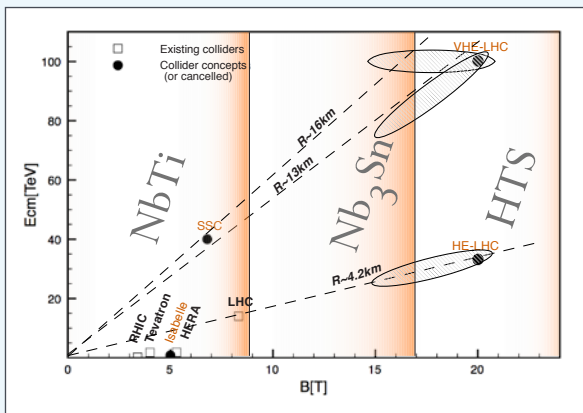
The latest upgrade to CERN's Large Hadron Collider is aimed at an order-of-magnitude increase in beam luminosity. Our primary role involves the final-focus quadrupoles that maximize the number of collisions. This will be the first major use of the brittle Nb₃Sn superconductor in an operating accelerator.



Photos courtesy G. Ambrosio (Fermilab) and P. Ferracin and E. Todesco (CERN).

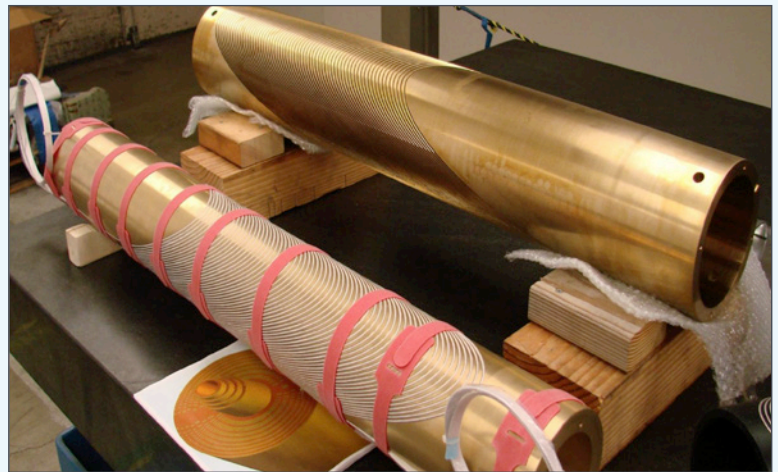
GOAL 3: NOVEL SUPERCONDUCTOR AND CAPABILITIES

Beyond state-of-the-art superconductor material development offers the hope of higher-performing magnets across a wide spectrum of Office of High Energy Physics and Office of Basic Energy Sciences programs and projects. This ongoing effort has already delivered on new and higher-performing superconductors and continues to do so. LBNL has managed the HEP Conductor Development Program throughout the last decade, and will continue to play a key role in defining the strategy for superconductor development in industry in the years to come in our role as lead lab for the HEP-supported U.S. Magnet Development Program (MDP).



DOE Conductor Development Program: Expanding the Most Fundamental Magnet Frontiers

The goal of this ongoing effort is to provide cost-effective, high-performance superconductors for the next-generation of high-energy physics (HEP) colliders. It is an industry-based national program that we manage on behalf of the DOE Office of High Energy Physics.



CCT Inner and Outer Layer Mandrels



Modified Groove Design



Program Area III: Advanced Concepts and Applications

BCMT seeks to identify areas where we can provide unique capabilities and expertise to the Office of Science through materials and magnets beyond the proven state of the art. Emphasizing systems that enable science capabilities beyond those of industry significantly leverages initial DOE and US investments. Projects benefiting from such advanced concepts likely include medical proton and carbon therapy facilities; ECR ion sources (VENUS, the Versatile ECR ion source for Nuclear Science, at LBNL, as well as ECR sources for the Facility for Rare Isotope Beams at Michigan State University, and for GSI); superconducting undulators; fixed-field alternating-gradient (FFAG) accelerators; fusion-energy magnets; and heavy-ion separators.

GOALS OF PROGRAM AREA III, ADVANCED CONCEPTS AND APPLICATIONS

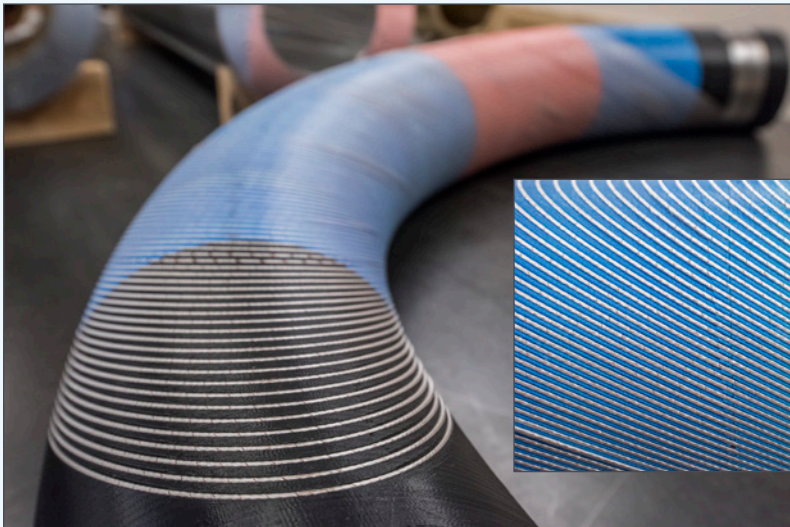
1. Pursue project-oriented R&D opportunities where beyond-state-of-the-art systems are necessary or highly advantageous.
2. Develop novel ECR source magnet designs and fabricate complete systems for DOE and partner institutions.
3. Develop superconducting accelerator magnet and gantry concepts for medical accelerators (proton and carbon therapy facilities), utilizing novel approaches such as canted-cosine-theta (CCT) magnet technologies to address cost, size, and weight considerations.
4. Superconducting undulator technologies for the next generation of light sources.

GOAL 1: PROJECT-ORIENTED R&D OPPORTUNITIES

Develop novel magnet designs, materials, and capabilities, needed to contain costs so that future colliders, smaller and lighter particle-therapy gantries, etc. can be realized.

GOAL 2: NOVEL ECR SOURCE MAGNETS

Design practical high-field ECR source magnets for VENUS, FRIB, and GSI, which will incorporate our latest Nb₃Sn technology.



Medical Gantries

The Canted Cosine-Theta (CCT) concept is being applied to medical therapy gantries together with collaborators Varian Medical Systems and the Paul Scherrer Institute. Goals: significantly reduce the need for magnet ramping during patient treatment, and reduce overall gantry weight an order of magnitude.



Magnets for ECR Ion Sources

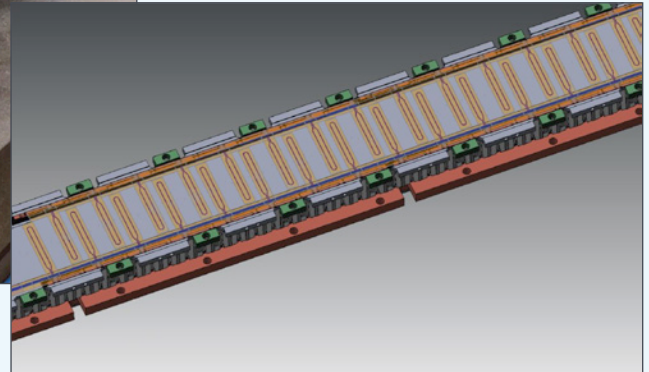
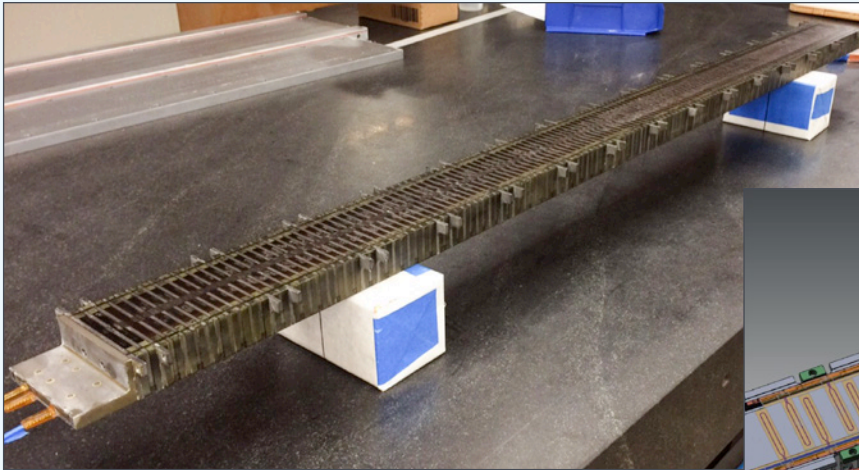
Electron cyclotron resonance ion sources provide intense beams of heavy ions at high charge states, but the field strength and magnet geometry pose challenges. The VENUS ECR source at LBNL's 88-Inch Cyclotron (shown here) led to the source for FRIB, DOE's flagship nuclear-science project.

GOAL 3: GANTRIES AND MEDICAL ACCELERATORS

Gantries in multi-room proton and carbon therapy facilities are dauntingly heavy and expensive, limiting development and implementation of new facilities. BCMT has developed several key technologies (such as CCT magnets and magnets for FFAG accelerators) that will greatly enhance the capabilities and reduce costs of new facilities.

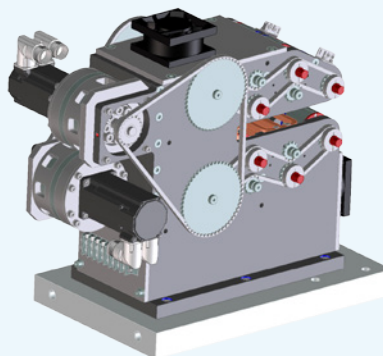
GOAL 4: SUPERCONDUCTING TECHNOLOGIES FOR LIGHT SOURCES

Extending spectral reach and expanding tunable range are keys to reducing the cost and enhancing the performance of any light source. Nb_3Sn superconducting undulators beyond the present state of the art offer the potential of achieving higher brightness in smaller and cheaper accelerators. BCMT's goal is to demonstrate this and make feasible prototypes available to the accelerator community.



Superconducting Undulator Technology for Light Sources

BCMT has been developing Nb_3Sn magnet technology — the conductor and new means for making magnets from this brittle material — for over two decades. Although it has mostly been applied to high-energy physics, it also has potential for advanced superconducting undulators.



Permanent-Magnet (PM) Systems for Storage Rings

Since the 1980s, LBNL has been a leader in PM accelerator magnets, undulators, and wigglers. From the world's first pure-PM and hybrid undulators, to today's hysteresis-free permanent magnet chicanes, to tomorrow's ultra-compact, tunable, pure PM systems, BCMT is at the forefront of PM applications.

Materials, Design, Fabrication and Test Infrastructure

Making our ideas a reality...

MATERIALS DEVELOPMENT

Progress in magnet development is strongly related to advances in materials. Our material development and characterization capabilities include strand critical-current testing, scanning electron microscopy, and measurements of tensile/compressive properties. We also have substantial expertise in testing high-current superconducting cables and maintain an active collaboration in this area with the National High Magnetic Field Laboratory, Brookhaven National Laboratory, Fermilab, and CERN.

A key asset of BCMT is our combination of expertise and facilities for the design and fabrication of superconducting cables (up to 60 strands). We have contributed NbTi cables to the LHC project through the US-LHC program and also in direct collaboration with CERN. We have developed and are fabricating cables for most of the Nb₃Sn accelerator magnet programs worldwide, such as the US LHC Accelerator Research Program (LARP), and will be providing all cables for the US-built magnets for the HiLumi-LHC project. We are also a world leader in the fabrication of Rutherford cables using the advanced high-temperature superconductor (HTS) wire Bi-2212.

DESIGN AND ANALYSIS

In order to address the technical challenges involved with advanced conductors and magnets, the program needs to continuously innovate in all areas of magnet design.

A fundamental component of this effort is related to the capability to accurately analyze and predict the magnet behavior using computer modeling. BCMT has assembled a broad set of tools that can be used on a multiplicity of magnet configurations. This suite comprises advanced software to carry out specific calculations, as well as interfaces to transfer input data and results across the various platforms. Advanced finite-element analysis (FEA) modeling is performed on magnetic systems to fully analyze electromagnetic and mechanical behavior, including AC losses, magnetization effects, mechanical stresses and strains, and interface conditions such as stick-slip and debonding. Advances in computer architectures, including the use of FEA on computer clusters, is allowing for significantly faster and more complex 3D analysis to be performed.

The most critical element of this activity is developing the expertise to correctly formulate and solve challenging coupled-field problems in magnet systems. In order to verify and improve the simulations, the analysis results need to be compared with detailed data collected during magnet testing, requiring advanced instrumentation and data acquisition capabilities. Modeling and instrumentation are both areas in which BCMT constantly seeks ways to improve its traditionally strong position.

MAGNET FABRICATION

The design and analysis phase is fully integrated with magnet fabrication and assembly through CAD engineering models, which can be used to either generate technical drawings or provide input to numerically controlled machines. Specialized facilities are available for coil winding; instrumentation of magnet systems; reaction and impregnation; fabrication of quench heaters and traces; magnet assembly and pre-load; and cable splicing. The fixtures for coil winding, reaction and impregnation can accommodate coils up to 4 meters in length.

The fabrication expertise accumulated by technicians and engineers over the years is one of the most valuable assets of BCMT. Our coil fabrication experience includes cos-theta, block, racetrack and solenoidal/helical windings. We also have experience in the fabrication of different types of mechanical support structures (collar-based, shell-based, etc.) and related assembly methods.

COLD TESTING

The Vertical Magnet Test station has standard capabilities for superconducting magnet testing, as well as special features relevant to high-field magnet R&D. These special features include the detection of fast voltage signals, providing insight into the origin of disturbances, such as conductor motions or flux jumps, which may limit magnet performance. The capability of accurately detecting these signals results from a long-term effort aimed at reducing the noise levels and improving the data acquisition systems.

BCMT CAPABILITIES

BROAD EXPERTISE, encompassing diversified magnetics and associated vacuum, cryogenic, mechatronic, and precision mechanical aspects, for partner programs at LBNL and other DOE facilities.

STATE-OF-THE-ART MEASUREMENT AND TESTING FACILITIES, encompassing measurement and testing, cryogenic, helium recovery, and quality control capabilities to foster design capability, characterization, testing, and tuning of conventional electromagnets, permanent magnets, hybrid, and superconducting magnets.

FABRICATION FACILITIES, including mechanical shops, coil winding, and ovens for high-quality magnet production of magnetics, cryogenics, mechanical, and vacuum system components.

QUALITY CONTROL capabilities, including coordinate measurement machines and QC procedures for magnet production.

PROJECT CONTROL AND ENGINEERING PROCESSES FRAMEWORK to execute projects efficiently and cost-effectively.

The cryogenic system includes a 200 W refrigerator, a vertical cryostat which can accommodate magnets with large cross section (80 cm) and length of up to 3 m, and additional vertical cryostats for smaller magnets. The main power supply can provide up to 24 kA, although current leads and the energy extraction system are presently limited to 15 kA. Magnetic measurements can be performed using a vertical rotating probe drive.

The magnet test facility has had a number of upgrades, and more are currently underway. These upgrades are intended to improve the quality of the data as well as the efficiency and safety of the operations. In particular, BCMT is planning to both upgrade the test facility and incorporate helium recovery technology. The upgrades will ensure reliability, and the He recovery system will reduce costs and help conserve a finite resource.

MAGNET MEASUREMENT FACILITY

BCMT's new Magnet Measurement Facility is a temperature-controlled, low-vibration/low-noise environment that enables the precise magnetics measurement and tuning necessary for optimal magnet performance. Our goal is to develop the facility's capabilities commensurate with the needs of the ALS, the proposed ALS-U, the current LCLS-II project, and beyond.

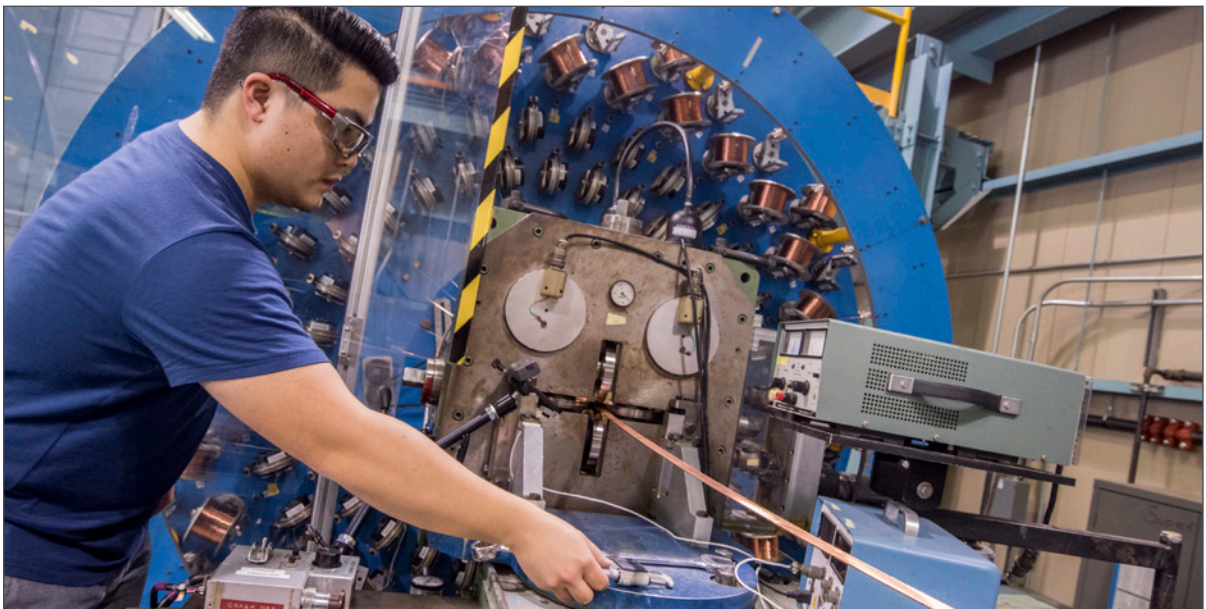
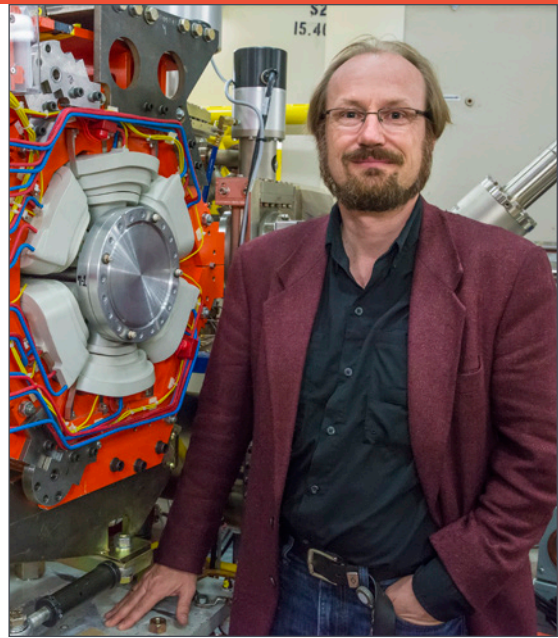
Key features being incorporated include a new Kugler granite measurement bench, as well as Hall probe, flip-coil, rotating coil, and pulsed-wire measurement capabilities. Provision for rapid lattice magnet and undulator side-access and closed small-bore (pulsed-wire and Hall-probe) measurement capabilities are being designed, fabricated, and installed. Finally, an automated Helmholtz coil for individual block measurement will round out the measurement suite.

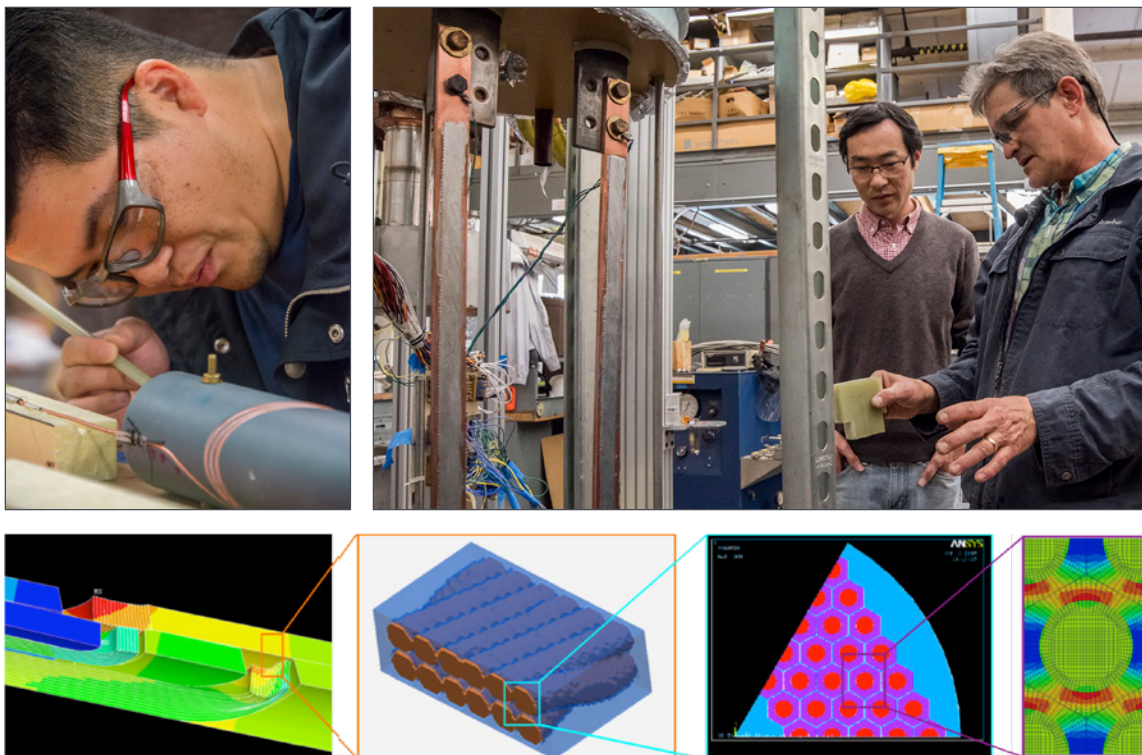
Fabrication, Quality Control, and Project Management Resources

LBNL's Engineering Division contributes many functions to BCMT beyond magnet design and conductor R&D and production.

- **THE ENGINEERING SYSTEMS GROUP** is vital in planning and executing BCMT projects. It supports BCMT with systems engineering, requirements management, configuration management, and applicable safety basis documentation. The Engineering Quality Assurance Group supports manufacturing processes.
- **THE ENGINEERING DIVISION** maintains several shops and assembly spaces to support projects during the manufacturing and assembly phases.
- **THE QA AND MANUFACTURING ENGINEERING GROUP** provides coordination for manufacturing, quality control, and supplier management to support BCMT projects as needed.

Clockwise from top left: Heng Pan examines an outer shell for a key-and-bladder magnet structure; Christoph Steier with one of the sextupole magnets for the Advanced Light Source Brightness Upgrade, a project under his technical leadership that won the Secretary of Energy Achievement Award; Daniel Cheng (foreground) and Ahmet Pekedis with a form for a prototype quadrupole for the Large Hadron Collider; Andy Lin at the machine that weaves superconducting cable from strands of wire.





Partnering and Technology Transfer

Arrangements for collaborative work, after your initial contact with the scientists and engineers involved, can be made with the help of the LBNL Innovation and Partnership Office (ipo.lbl.gov). They also handle the licensing of existing technologies and are familiar with the LBNL portfolio of tools and techniques that you can put to work.

BERKELEY CENTER FOR MAGNETIC TECHNOLOGY

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