The National High Magnetic Field Laboratory (National MagLab) remains the world's largest and highest-powered magnet lab. A multi-disciplinary user facility, the National MagLab provided high magnetic field access to more than 9,240 researchers between 2018 and 2022. These scientists used the National MagLab's powerful magnets – instruments more than a million times more powerful than the Earth's magnetic field – to investigate new materials, find energy solutions, protect the environment, understand diseases to improve health, and answer other important interdisciplinary research questions, publishing more than 2,000 peer-reviewed publications.

Magnets Explore New Materials

New technology and devices require **new materials,** and magnets help discover and explore the electronic properties of new materials, unlocking behaviors that might be of technological importance. Magnetic fields have been vital to the development and understanding of electronics, lasers and fast optical switches used in the Internet, materials that have enabled products that have changed your life- and will continue to change it in ways we cannot yet imagine.

Researchers made important foundational discoveries on materials during this project period:

- A hydrogen-packed compound squeezed to ultra-high pressures superconducts tantalizingly close to room temperature (as "warm" as -10 degrees Fahrenheit or -23 degrees Celsius).
- In a uranium-based compound, scientists watched superconductivity arise, perish, then return to life under the influence of high magnetic fields.
- A technique to manipulate the electrical conductivity of graphene with compression takes the material one step closer to being a viable semiconductor for use in today's electronic devices
- A unique way to bond together atomically thin semiconductors yields high-quality structures that scientists can use to develop new nanotechnologies and prototype diodes and photovoltaic cells.
- Researchers discovered a behavior in materials called cuprates that suggests they carry current in a way entirely different from conventional metals such as copper, adding new meaning to their moniker, "strange metals."
- Two properties that are rarely measured in the same material -— "metamagnetism" and "low-carrier Kondo" effects — were measured in $YbRh_3Si_7$.
- With a twist and a squeeze, researchers discover a new method to manipulate the electrical conductivity of graphene, a game-changing "wonder material."
- A class of materials called "1-2-20s" (one-two-twenties) were shown to have very promising thermoelectric properties offering scientists a key to materials that can turn heat into electricity, and vice versa.
- An unusual metallic state was unlocked when scientists sought to turn superconductivity off in "stripe-ordered" cuprates — copper-oxide materials with alternating areas of electric charge and magnetism. Under the conditions of their experiment, even after the material lost its ability to carry electrical current with no energy loss, it retains some conductivity — and possibly the electron (or hole) pairs required for its superconducting superpower.
- A new study reveals a suite of quantum Hall states that have not been seen previously in double-layer stacks of graphene, a two-dimensional nanomaterial, shedding new light on the nature of electron interactions in quantum systems and establishing a potential new platform for future quantum computers.
- Researchers observed, characterized, and controlled dark trions in a semiconductor — ultraclean single-layer tungsten diselenide (WSe_2) — a feat that could increase the capacity and alter the form of information transmission.
- A quantum fluid—fractional quantum Hall states, one of the most delicate phases of matter—was discovered in a monolayer 2D semiconductor, a finding that could provide a unique test platform for future applications in quantum computing.
- Evidence for a quantum spin liquid, a state of matter that is promising as a building block for the quantum computers of tomorrow was seen in the compound ruthenium trichloride ($RuCl_3$).
- Theory and experimental research teamed up to yield the first direct evidence of the nature of superconductivity in a promising material called magic-angle twisted bilayer graphene.

- An exotic new phase of matter was seen on an unusual Kondo insulator ytterbium dodecaboride (or YbB_{12})
- MagLab researchers managed to visualize the vortex tubes in a quantum fluid, findings that could help researchers better understand turbulence in quantum fluids and beyond.
- Researchers defined calculation framework to explain why electrons traveling in any direction in a strange metal follow the "Planckian limit."
- Adding a piece to the 30-year-old puzzle surrounding high-temperature superconductors, researchers found that magnetism is key to understanding the behavior of electrons in these zero-resistance materials.
- MagLab users have modified the critical current of Nb_3SN, a material that was thought to be fully exploited, and boosted its performance by 50%.
- A nematic phase is where the molecular/atomic dynamics show elements of both liquids and solids, like in liquid crystal displays on digital watches or calculators. Using high magnetic fields and high pressure, researchers probed the electronic states of an iron-based superconductor and found that its nematic state weakened superconductivity.
- Researchers demonstrate a new record magnetoresistance in graphene by improving the contacting method, which helps improve our understanding of the material and can be useful in future sensors, compasses and other applications.
- Using far-infared magnetospectroscopy in high magnetic fields, scientists probed coupled electronic and vibrational modes in a molecular magnet that are of interest in future classical and quantum information applications.

Magnets Fuel Energy Discoveries

High magnetic fields are an essential tool for addressing a wide range of energy challenges related to creating, storing and conserving energy.

During this project, researchers used high magnetic fields to fuel discoveries about existing energy sources and explore new ones:

- Work to examine the nanoscale assembly of components in multiple plant species, including grasses, hardwood, and softwood species revealed how carbohydrates interact to form plant biomass. This new information can help advance the development of better technology to use biomass for energy and materials.
- New research on one of the most economically important agricultural plants in the U.S. - corn - has revealed a different internal structure of the plant than previously thought. The surprising discovery, made with the help of powerful magnets at the National MagLab could help optimize how corn is converted into ethanol.
- A new way to stabilize the color of light being emitted from a promising class of next-generation materials was discovered that could be the basis for efficient and more cost-effective optoelectronic technologies that can turn light into electricity or vice versa.
- Research showed that batteries built from inexpensive and safe components can deliver three to four times the punch of batteries built with today's state-of-the-art lithium-ion technology.
- A new method to characterize crude oil corrosion shows that corrosion in acidic crude oils depends on the specific structures of the acid molecules, information that can help improve oil valuation and refining.
- For the first time, scientists showed that high-field nuclear magnetic resonance can be combined with single crystal infrared (IR) microscopy to quantify and understand microscopic gas transport in a novel class of porous molecular sieves called zeolitic imidazolate frameworks (ZIFs). These “molecular sieve” materials are highly promising candidates for gas separation applications and could lead to much cheaper gas production.

Magnets Protect the Environment

Magnets at the MagLab offer the ability to analyze exceptionally complex mixtures with amazing precision – a tool that is impactful to understand the makeup of the many complex mixtures that exist in our world.

These discoveries leveraged powerful magnets or specialized techniques to make novel discoveries about our environment:

- Using tools at the MagLab, scientists pinpointed pigments that are the oldest on record.
- Research showed that exposure to sun and water causes thousands of chemicals to leach from the asphalt binder in roads into the environment.
- Scientists discovered that older dissolved organics from deforested areas were more energy-rich, and potentially more harmful to the planet.
- Using one of the most powerful chemical analysis tools in the world, scientists are working to characterize and catalog the thousands upon thousands of chemical compounds in the “Forever chemical” PFAS family, so future studies can find solutions to both health and environmental impacts.
- Researchers provided fresh evidence that, while most of the Earth's crust is relatively new, a small percentage is actually made up of ancient chunks that sunk back into the mantle long ago then later resurfaced. They also found, based on the amount of that "recycled" crust, that the planet has been churning out crust consistently since its formation 4.5 billion years ago — a picture that contradicts prevailing theories.
- A link between prehistoric volcanism, loss of oxygen and mass extinction has long been suspected, but a MagLab study provided the first conclusive data and provide a greater understanding how Earth systems respond to climate change.
- Discoveries showed that sunlight can chemically transform plastics from consumer plastic bags into complex chemical mixtures that leach into the ocean. Understanding the impact of plastic pollution requires advanced analytical techniques that can identify transformed plastic molecules in water samples and required instrumentation only available at the MagLab.
- Analysis on the organic composition of peat wetland soils can help determine whether the carbon sources may be converted into carbon dioxide gas, work that could improve existing climate models and better predict the impact of increasing carbon dioxide to wetland ecosystems.

Magnets Understand Disease to Improve Health

Magnetic fields are the force behind MRI- **magnetic resonance imaging** – the diagnostic instruments found in hospitals and doctor’s offices. Most hospital MRIs have a magnetic field around 1.5 tesla, but the National MagLab’s uses a 21 tesla MRI and other powerful tools to make critical discoveries on diseases.

Our customized magnet systems allow scientists to study everything from whole, living animals to individual cells to tiny disease proteins, leading to exciting health-related discoveries during this project period:

- A link between migraines and how sodium is distributed through the brain was discovered, a finding that could be a key to future research on treatments for migraine sufferers.
- An ability to detect a signal from a gramicidin oxygen that was bound to the water wire, and a *separate* signal from a gramicidin oxygen that was *not* bound to the wire, researchers determined that the interactions between the water wire and pore wall of the gramicidin A were much stronger and longer-lasting — more than a *million* times longer, in fact — than scientists had believed.
- Work revealed the molecular architecture of fungal cell walls and the structural responses to stresses, aiding the development of antifungal drugs targeting cell wall components. Life-threatening fungal infections impact the health of millions of humans each year and with limited efficacy of some commercially available drugs, a need for novel antifungal compounds is on the rise.
- High-field magnetic resonance images present a possible pathway for metabolic waste removal from the brain and suggests that waste clearance may be one reason why we sleep.
- Researchers polarized the protons of hydrogen atoms in water, effectively boosting its magnetic properties. The resulting “hyperpolarized water” is far more sensitive to MRI detection than regular water and suggest the liquid could be used to create MRI images using magnets that are far cheaper and smaller than what are currently needed.
- A high-field EPR study of the bacterium Deinococcus Radiodurans provides the strongest known biological indicator of cellular ionizing radiation resistance between and within the three domains of the tree of life, with potential applications including optimization of radiotherapy.

- Scientists refined a technique called mass spectrometry imaging (MSI) that translates reams of data into detailed visuals of the molecular makeup of biological samples producing images with mass resolution so high that every color in the image represents a unique kind of molecule.
- Scientists measured the first *in vivo* images of stimulated current within the brain using an imaging method that may improve reproducibility and safety and help understand the mechanisms of action of electrical stimulation.
- The causes of migraines are not well understood, with treatment limited to addressing pain rather than its origin. Research conducted with hydrogen MRI is attempting to identify the "migraine generator."
- Researchers found new potential disease markers for brain tumors. The scientists used a novel image contrast technique called chemical exchange saturation transfer (CEST), as well as advanced signal processing algorithms, to acquire detailed images.
- Scientists studied the cells' surface proteins, called T-cell antigen receptors (TCRs), measuring their molecular movements relevant to immune system activation. They learned how a surface protein responds to outside signals to activate immune responses and attack diseased cells.
- A comprehensive, fast, and accurate characterization of hemoglobin for clinical diagnosis of human blood was performed using the unique capabilities of the MagLab's 21T Fourier Transform ICR mass spectrometer.
- Magnetic Resonance Imaging of mouse models for Alzheimer's disease can be used to determine brain response to plaque deposits and inflammation that ultimately disrupt emotion, learning, and memory. Quantification of the early changes with high resolution MRI could help monitor and predict disease progression, as well as potentially suggest new treatment methods.
- Magnetic resonance of cancer cell metabolism is a novel technique to discern between cancerous and normal liver cells, providing a promising approach for cancer stage progression imaging without the harmful exposure of radiation.
- The MagLab contributed heavily to the creation of a **Blood Proteoform Atlas** which maps 30,000 unique proteoforms as they appear in 21 different cell types found in human blood.
- Non-alcoholic Fatty Liver Disease and its progression to more serious diseases will become the main cause for liver transplant in the next 5 years. Researchers used deuterium magnetic resonance to study dietary influences on lipid synthesis and demonstrated that high fat ketogenic diets significantly slow de novo lipogenesis, a process by which excess carbohydrates are covered into fatty acids and stored as triacylglycerols.
- MRI scans taken after a stroke show brightness around the injury, the origins of which have been a long-standing and vexatious mystery for scientists. New work suggests these MRI signal changes result from fluid changes in glial cell volumes, results that could advance our ability to distinguish reversible and irreversible stroke events or provide a better understanding for other disorders such as Parkinson's, Alzheimer's, and mood or sleep disorders.
- Using NMR, researchers determined a molecular model of a protein-polymer conjugate, providing new insights into how polymers can be used to make protein drugs more robust.

Magnet Technology

Home to more than a dozen world-record magnet systems, MagLab researchers and engineers work to advance magnet technology, pushing research tools at the MagLab and beyond to new heights and facilitating exciting advances and discoveries. These highlights emphasize the magnet technology advancements and notable moments during this grant:

- Engineers and technicians from the National High Magnetic Field Laboratory were recognized with a **2022 R&D 100 Award** for the design and construction of the 32 tesla (T) Superconducting Magnet.
- With a mini no-insulation magnet coil, engineers at the MagLab achieved 45.5 tesla in a test coil, a world-record magnetic field that could lead to a new generation of magnets for biomedical research, nuclear fusion reactors and many other applications.
- A new kind of magnet featuring Conductor on Round Core (CORC®) cable was tested, paving the way for a technology that could be used in next-generation particle accelerators and compact fusion machines.

- MagLab researchers found that adding the element Hafnium to a Niobium (Nb)-Tantalum (Ta) base alloy to form the superconductor Nb_3Sn after a reaction with Tin (Sn) at high temperatures can lead to 60% more electrical current carrying ability of the conductor wire.
- A novel use of high-resolution scanning electron microscopy helped researchers understand more about how processing methods influence grains and can improve the performance of bismuth-based high-temperature superconducting wires (Bi-2212), findings that have the potential to power a new generation of particle accelerators.

Education, Outreach & Broadening Participation

The National MagLab also grows a new generation of scientists through many education and outreach programs that get students interested in careers in science, technology, engineering and mathematics. Educational outreach was provided to more than 7,400 K-12 students with another nearly 600 students participating in a long-term mentorship, camp or research program. From 2018 through 2022, more than 29,000 visitors attended an Open House event, visiting about the lab and exploring the fun of hands-on science.

During this project period, hundreds of undergraduate and graduate students were trained as students at the lab or through the MagLab user program with the lab contributing to about 100 PhD and masters' theses. More than 600 early career scientists attended a MagLab User Summer or Winter Theory School in the past five years. Participation in high magnetic field research continues to expand with users from 23 out of 28 EPSCOR locations. During this five-year grant period, 5.5% of MagLab users were from Minority Serving Institutes – 1% HBCU and 4.5% HIS.