# SLAC+Stanford 2016

SLAC NATIONAL ACCELERATOR LABORATORY

# SLAC

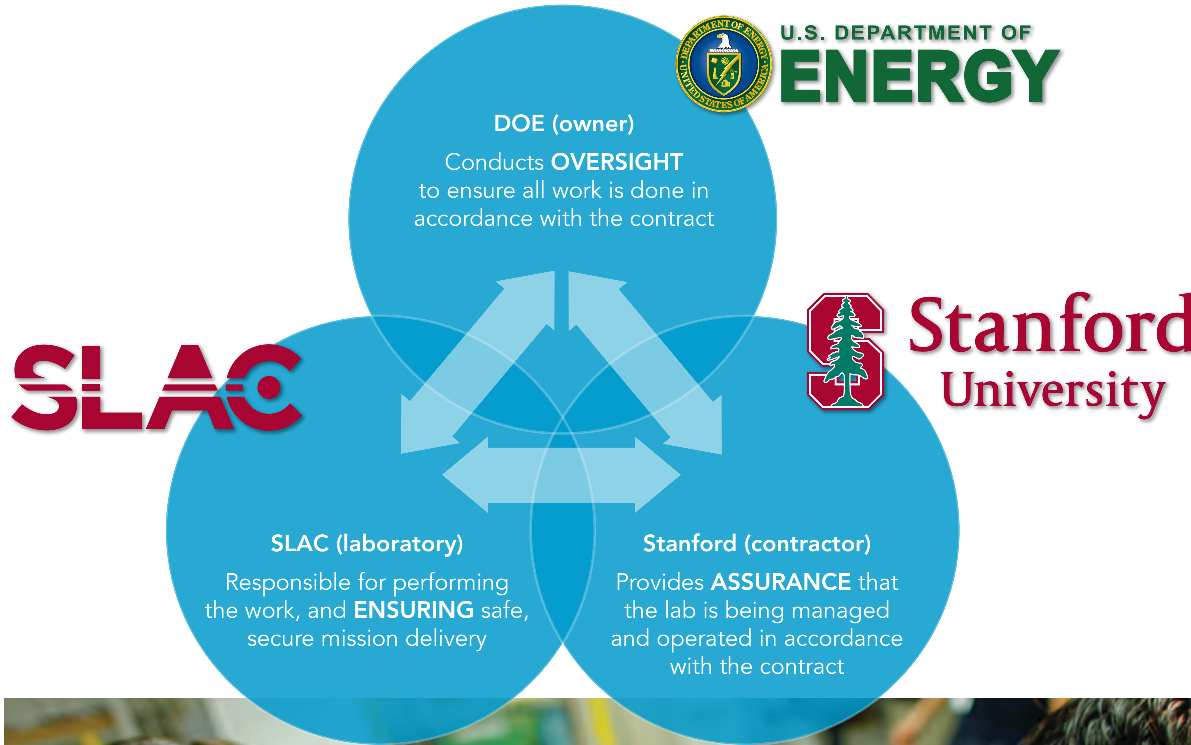
Founded in 1962 with a 2-mile-long linear accelerator used for revolutionary high-energy physics experiments, SLAC has evolved into a multi-program laboratory whose mission leverages its intellectual capital, unique relationship with Stanford University and location within Silicon Valley. As one of 17 Department of Energy national laboratories, we are part of the most comprehensive research system of its kind in the world.

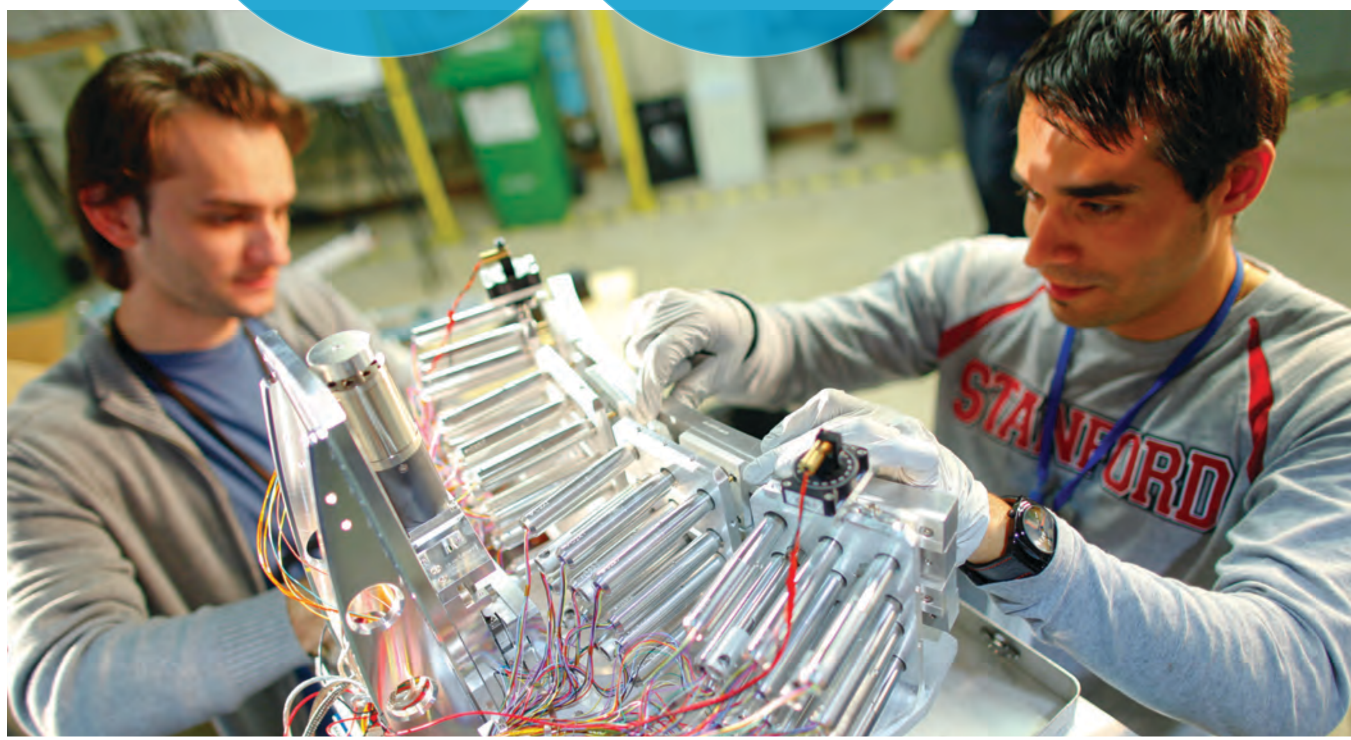
# DOE

SLAC operates three DOE Office of Science "user facilities" that host thousands of researchers from around the world each year. The research we carry out, and the technology we invent and develop, support the DOE mission of ensuring America's security and prosperity by addressing the nation's energy, environmental and nuclear challenges.

# STANFORD

Stanford University operates SLAC for the Department of Energy's Office of Science. We sit on 426 acres leased from the university; our people are Stanford employees; and our faculty teach and mentor Stanford graduate students, helping to train the next generation of scientists. Stanford is an important source of intellectual power for conducting research at SLAC and planning the lab's next generation of facilities, and we coordinate our planning with major Stanford initiatives.



# A Message From the Director

No other Department of Energy national laboratory enjoys such a close relationship with a great university as SLAC does with Stanford. Our ties go all the way back to a crucial meeting, 60 years ago next month, where a group of visionary Stanford physicists began to plan the construction of a 2-mile-long linear electron accelerator in the foothills west of campus.

That accelerator, built on land leased from Stanford, would become the heart of SLAC. The professor who hosted the meeting, W. K. H. "Pief" Panofsky, would become SLAC's first director. And the bond that was forged between SLAC and Stanford would only get stronger over time.

Today the university manages SLAC for the DOE Office of Science. Our staff members are Stanford employees. Our faculty teach on campus and mentor Stanford graduate students and postdocs, who come here to train and do research at our unique facilities. And as you'll see in this report, our scientific programs increasingly intertwine with Stanford's, allowing both sides to achieve much more than they could on their own.

For instance, Stanford benefits from our core expertise in lasers, detectors and accelerators, and from having SLAC's three world-class user facilities, for X-ray science and advanced accelerator research, just up the road. Two of the joint initiatives described in this report – a system prototyping laboratory and the Macromolecular Structure Knowledge Center – have the explicit purpose of making it easier for Stanford researchers to get help with their projects from SLAC experts.

SLAC, in turn, is able to leverage the intellectual power and specialized facilities on campus, as well as the university's connections to Silicon Valley and its ability to raise private funding for important projects, such as the Photon Science Laboratory Building we now have under construction. This three-story, 105,000-square-foot building will give us the space we desperately need to accommodate our growing number of outside users and enhance our expanding collaborations with Stanford in materials science, chemistry, biology and energy science.

PSLB isn't the only high-priority lab project with considerable Stanford connections. You'll find a number of examples in this report, from construction of the world's biggest digital camera for a sweeping and unprecedented survey of the sky to initiatives aimed at improving batteries, finding smarter ways to manage the power grid, building a particle accelerator the size of a shoebox and enhancing our research computing capabilities. Many of these involve one of the four joint institutes we operate with the university. On the far horizon, LCLS-II, a significant upgrade of our world-leading LCLS X-ray laser, will be an exciting, one-of-a-kind resource for researchers at SLAC, Stanford and around the world.

We hope this brief report serves as a general introduction to SLAC and its programs, as well as the first in a series of annual snapshots documenting the lab's growing portfolio of projects and initiatives with Stanford.

*Chi-Chang Kao*
*Director, SLAC National Accelerator Laboratory*
*March 2016*

# SLAC at a Glance

SLAC is one of 17 Department of Energy national laboratories, operated by Stanford University for the DOE Office of Science. From our roots in particle physics, we have evolved into a multipurpose laboratory that also includes research programs in materials, chemical, biological and energy science, matter in extreme conditions, cosmology and technology development. We welcome thousands of scientists each year to do research at our world-class user facilities, including the world's first hard X-ray free-electron laser. Our strong and growing partnership with Stanford is a key factor in our success.

## STATS & FACTS

**Founded: 1962**

**Site: 426** acres leased from Stanford

**Staff: 1,450** employees

**Facility Users:** More than **2,700** per year, including **350** from Stanford

**Annual Budget, FY15: $433 million**

**Core Expertise:**

- Accelerators
- Detectors
- X-rays
- Lasers

### Scientific Focus

- Materials Science
- Chemical Science
- Bioscience
- Plasma and Fusion Energy Science

**Energy:**

- Batteries
- Solar Energy
- Catalysis

**High-energy Physics:**

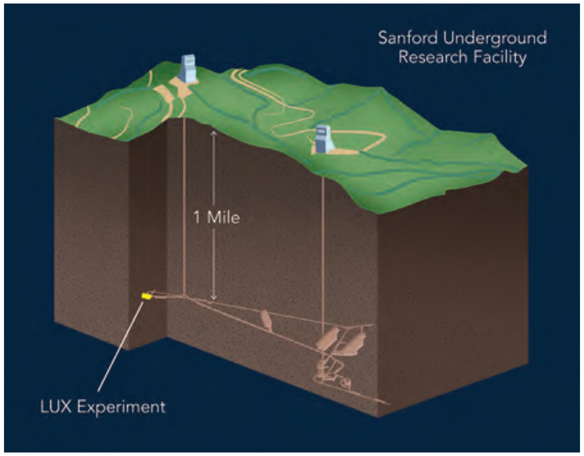
- Dark Energy
- Dark Matter
- Cosmic Inflation
- Particle Physics

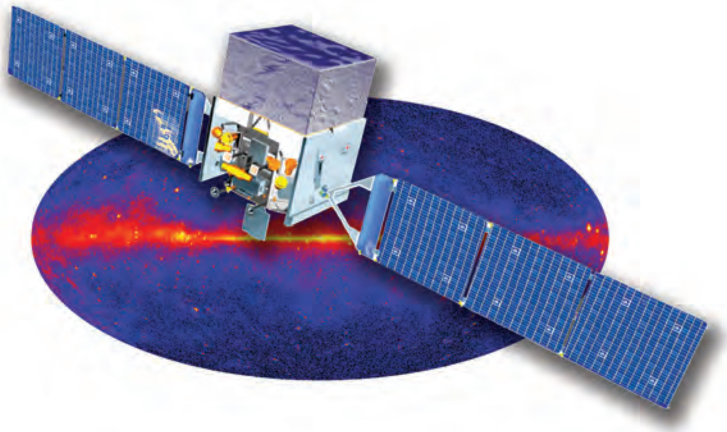
# By the Numbers

SLAC's highest experiment, the Fermi Gamma-ray Space Telescope, looks for gamma rays while orbiting 350 miles overhead.

At 3,073.72 meters (1.9 miles) long, our linear accelerator is the longest modern building on Earth. Electrons zip down the linac at 669,600,000 mph – 99.9999999 percent of the speed of light. Constructed more than 50 years ago for particle physics experiments, the linac now generates high-energy electrons for advanced accelerator research and the LCLS X-ray laser.

SLAC's deepest experiment, LUX, hunts for dark matter in a former gold mine 4,850 feet below ground in South Dakota.



Our farthest look back in time is BICEP, an array of sensors near the South Pole that searches for patterns left by cosmic inflation in the first trillionth of a trillionth of a trillionth of a second after the Big Bang.

(Steffen Richter, Harvard University)

# Joint Institutes and Centers

We run four joint research centers with Stanford that have operations on both campuses; they received a total of ~$44 million in DOE funding in FY 2015. The joint institutes promote interactions between SLAC and Stanford and are an important source of training for young scientists.

(Reidar Hahn/Fermi)

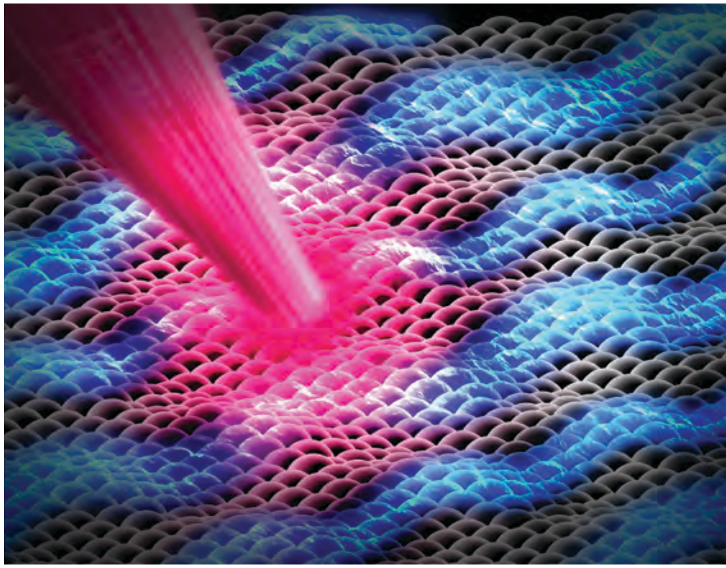
## Kavli Institute for Particle Astrophysics and Cosmology

**FY15 DOE funding: ~$19 million**

KIPAC is a Stanford independent laboratory whose members work in the Stanford physics and applied physics departments and at SLAC. It brings the resources of modern computational, experimental, observational and theoretical science to bear on our understanding of the universe at large.

### On the Hunt for Dark Matter

KIPAC scientists play key roles in two upcoming dark matter searches: LZ, which is scheduled to start collecting data in 2019, and SuperCDMS-SNOLAB, which should start in 2018. Both will be deep underground to shield them from interfering signals. Dark matter is thought to constitute 85 percent of the mass in the universe, but so far it's been detected only indirectly, through its gravitational influence on the matter we can see. The exquisitely sensitive germanium detectors at the heart of SuperCDMS-SNOLAB will be assembled at SLAC from parts fabricated around the country. LZ's detector will contain 10 metric tons of ultra-pure liquid xenon; SLAC is in charge of purifying that xenon and will assemble and test a detector prototype.



## Stanford PULSE Institute

**FY15 DOE funding: ~$5 million**

PULSE is a Stanford independent laboratory and SLAC research center. It uses SLAC's LCLS X-ray laser as a primary tool for advancing the frontiers of ultrafast science.

### New Wrinkles in Behavior at Ultrafast Speeds

PULSE researchers were heavily involved in the development of SLAC's new Ultrafast Electron Diffraction instrument, UED. The first published study from UED revealed individual atoms moving in about a trillionth of a second to form wrinkles in a three-atom-thick layer of molybdenum disulfide. This unprecedented level of detail could help guide development of efficient solar cells, fast and flexible electronics and high-performance chemical catalysts. In other studies with the LCLS X-ray laser, PULSE researchers watched nanoscale semiconductor crystals expand and shrink in response to powerful pulses of light, and discovered that at very high intensities, X-rays stop behaving like the ones in your doctor's office and begin interacting with matter in very different, "nonlinear" ways.

## Stanford Institute for Materials and Energy Sciences

FY15 DOE funding: ~$14 million

SIMES studies the nature, properties, interactions and synthesis of complex and novel materials, and doubles as the Materials Science Division of SLAC.

### Putting Silicon Particles in Graphene Cages Boosts Battery Performance

Scientists would like to use silicon in lithium-ion battery anodes because of its high capacity for storing charge. But it swells and breaks up during charging and also reacts with the electrolyte, sapping its performance. SIMES researchers found a potential solution: Wrap each silicon anode particle in a microscopic cage made of graphene. The cages are roomy enough to allow the silicon particles to swell and strong enough to hold the pieces together when they break apart. In tests, the cages enhanced the silicon anode's conductivity and provided high charge capacity, chemical stability and efficiency.

## SUNCAT Center for Interface Science and Catalysis

FY15 DOE funding: ~$6 million

A partnership between SLAC and the Stanford School of Engineering, SUNCAT explores challenges associated with the atomic-scale design of catalysts for chemical transformations of interest for energy conversion and storage.

### Atom-Sized Craters Make Catalyst More Active

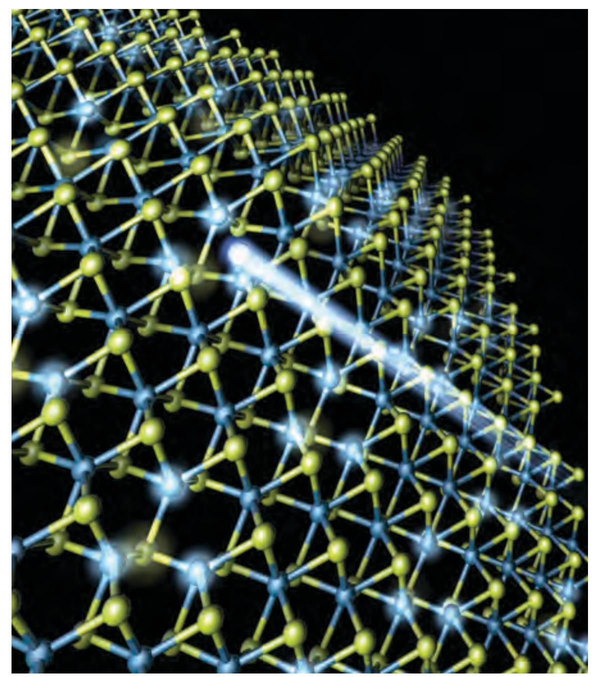
Bombarding and stretching an important industrial catalyst opens up tiny holes on its surface where atoms can attach and react, greatly increasing its activity as a promoter of chemical reactions, according to a study by scientists at Stanford, SUNCAT and SIMES. The catalyst, molybdenum disulfide, helps remove sulfur from petroleum in refineries and could be a good alternative to platinum as a catalyst for a reaction that generates hydrogen gas for fuel. The method should also work with other catalysts.

## SLAC+PIE and ChEM-H

SLAC scientists are also deeply involved in two other Stanford institutes.

The Precourt Institute for Energy (PIE) is a hub for experts in many disciplines who are working to solve the world's most pressing energy problems. Seven SLAC faculty and staff scientists are members of the institute, which holds an annual conference, Energy@Stanford & SLAC, to introduce incoming Stanford graduate and professional school students to opportunities on both campuses.

ChEM-H is an interdisciplinary institute founded by the Stanford schools of Humanities and Sciences, Engineering and Medicine. It promotes research aimed at understanding life at a chemical level and applying that knowledge to improving human health. Half a dozen SLAC/Stanford faculty members are institute fellows. (See Macromolecular Structure Knowledge Center, page 11.)



(Charlie Tsai/Stanford University)

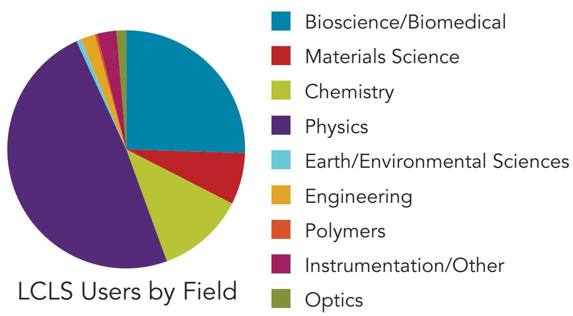
# SLAC → Stanford

SLAC's unique facilities and expertise in key areas of science and technology complement what's available at Stanford, accelerating research on both campuses. Of the 2,700 scientists who used our three DOE Office of Science user facilities in FY15, 13 percent were from Stanford. We also play an important role in teaching and mentoring Stanford students.

## SLAC's World-class User Facilities

### Linac Coherent Light Source

The world's first hard X-ray free-electron laser, LCLS illuminates objects and processes at unprecedented speed and scale for research in materials science, chemistry, structural biology, energy science, physics and other fields. A major upgrade now underway, LCLS-II, will greatly increase its brightness, its firing rate and the number and variety of experiments it can perform.



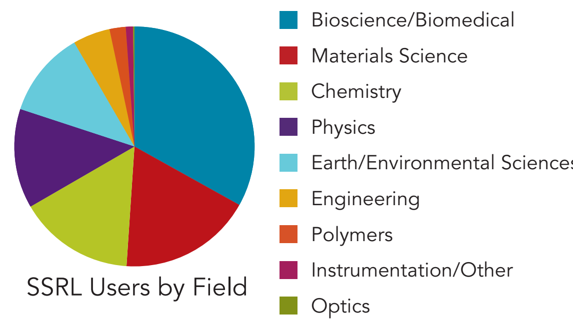
LCLS Users by Field

### Facility for Advanced Accelerator Experimental Tests

FACET hosts experiments aimed at improving the power and efficiency of particle accelerators used in basic research, medicine, industry and other areas important to society.

### Stanford Synchrotron Radiation Lightsource

SSRL produces bright X-ray light for probing matter at the atomic and molecular level, enabling advances in energy production, environmental cleanup, nanotechnology, new materials and medicine. SSRL science has produced more than 12,000 publications since its inception.



SSRL Users by Field

## First Endowed Professorship Linking SLAC, Stanford

In 2015, Stanford and SLAC established the first endowed professorship that is reserved specifically for joint appointments between the two. The Wallenberg-Bienenstock Professorship honors Arthur I. "Artie" Bienenstock, professor emeritus and former director of the SLAC synchrotron facility. This professorship is expected to attract a top-notch science or engineering faculty member and further strengthen ties between the university and the lab.

## Panofsky Fellowship Expanded

SLAC recently expanded its prestigious Panofsky Fellowship for early career scientists to encompass all areas of science performed at the laboratory. These 5-year fellowships are intended to attract high-quality, innovative young scientific staff who could potentially lead new science programs at the laboratory.

## SSRL Structural Biology: The SLAC-Stanford Synergy

One of the strongest science synergies between Stanford and SLAC is in structural biology. More than 30 Stanford faculty groups in 15 departments within the schools of Medicine, Humanities and Sciences, and Engineering pursue research enabled by SSRL's eight structural biology beamlines. Topics include neuroscience, GPCRs, transcription, infectious diseases and drug discovery. Stanford has invested in two of these beamlines. The National Institutes of Health and the DOE's Biological and Environmental Research program, along with Stanford and other non-federal sources, have provided more than $200 million in direct funding in the last 15 years alone, enabling pioneering innovations that keep these facilities at the forefront for SSRL's large national and international user community.

# Faculty and Teaching:

SLAC provided $10 million toward the scientific studies of nearly 300 Stanford graduate students and postdocs in FY15, along with unique research opportunities in our laboratories. Our faculty taught 30 courses in six Stanford departments in the 2014-15 academic year.

SLAC faculty: 55
(including 25 joint with Stanford)

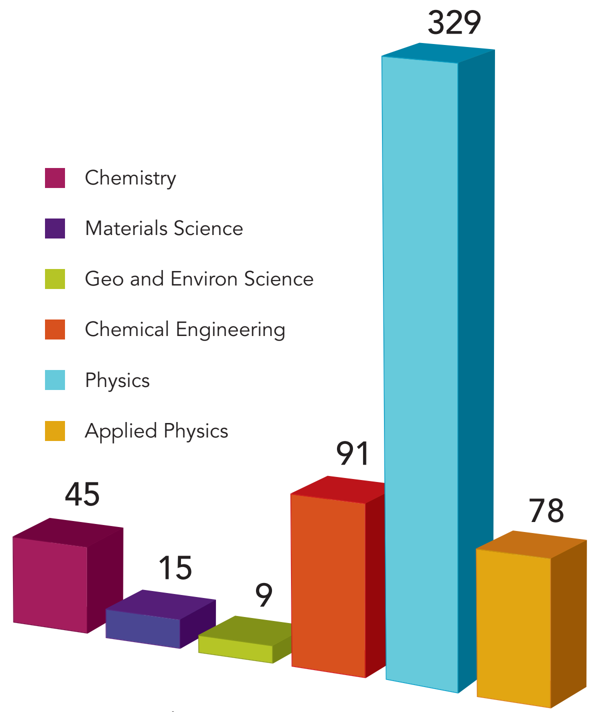
Graduate students: 167

Postdoctoral researchers: 119

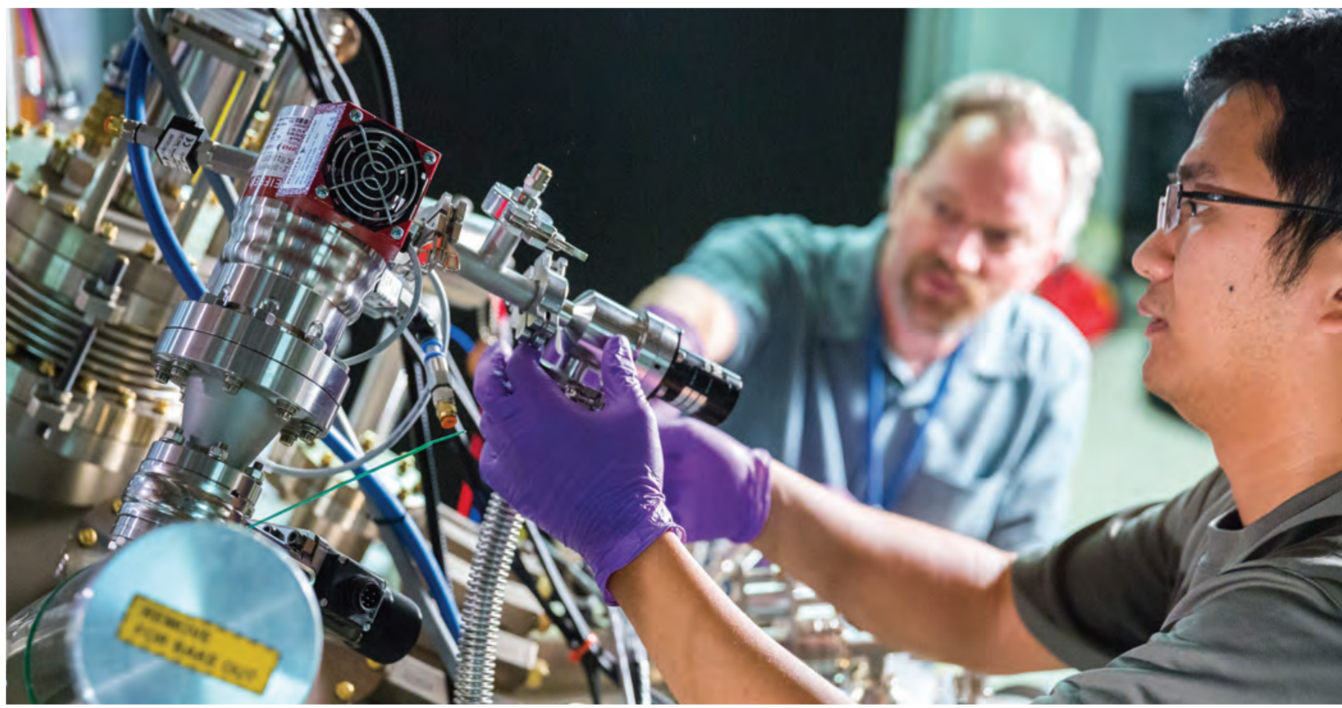
Courses taught, 2014-15: 30

Students enrolled in those courses: 567

PhDs awarded: 27




Students per Department



# Stanford → SLAC

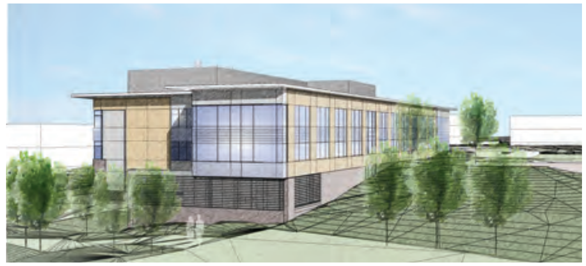
Stanford is an important source of intellectual power for SLAC, and supports the lab in numerous ways. SLAC staff members are Stanford employees with a wide range of benefits. Stanford also provides SLAC with facilities and services that ease the administrative burden on the lab.

## Photon Science Laboratory Building Rises at SLAC

This three-story, 105,000-square-foot building will provide much-needed space for the lab's growing portfolio of research in materials, chemical, biological and energy sciences and other areas. It will enhance collaborations between SLAC and Stanford scientists and bring them into close contact with experts in developing lasers, detectors, optics and other tools they need. Stanford is constructing the shell of the building with donated funds, and construction is projected to finish in late 2016. DOE will fit out the first two floors, and SLAC is working with Stanford to raise funds for equipment.

## New LCLS Instrument for Bioscience

The Macromolecular Femtosecond (X-ray) Crystallography instrument, or MFX, was specially designed for determining the molecular structure of biological molecules, although it can be used for a variety of experiments. Its atomic-resolution X-ray images and ultrafast movies of molecules in action will help researchers find new ways to fight disease and unravel the secrets of photosynthesis and other crucial biological processes. MFX will also increase the number and efficiency of experiments at LCLS, and will work in tandem with a new X-ray beamline at SSRL to be built in part with Stanford funding. The new MFX instrument was funded by the DOE, Stanford, the National Institute of General Medical Sciences and Howard Hughes Medical Institute.



## Research Computing Gets Major Upgrade

SLAC is investing up to $3 million in a major hardware upgrade for the Stanford Research Computing Facility, a high-performance computing data center built by the university on the SLAC campus. Opened in 2013, it's used by more than 230 principal investigators and 1,100 students. The upgrade is being carried out through a collaboration of the four joint institutes – KIPAC, SUNCAT, PULSE and SIMES – with additional support from the Stanford Dean of Research. It will benefit research computing across the many fields the institutes cover, from quantum chemistry, catalysis and material design to cosmology, ultrafast processes and the dynamics of dark matter.

## STANFORD FUNDING

### SLAC Facilities Built/Funded by Stanford

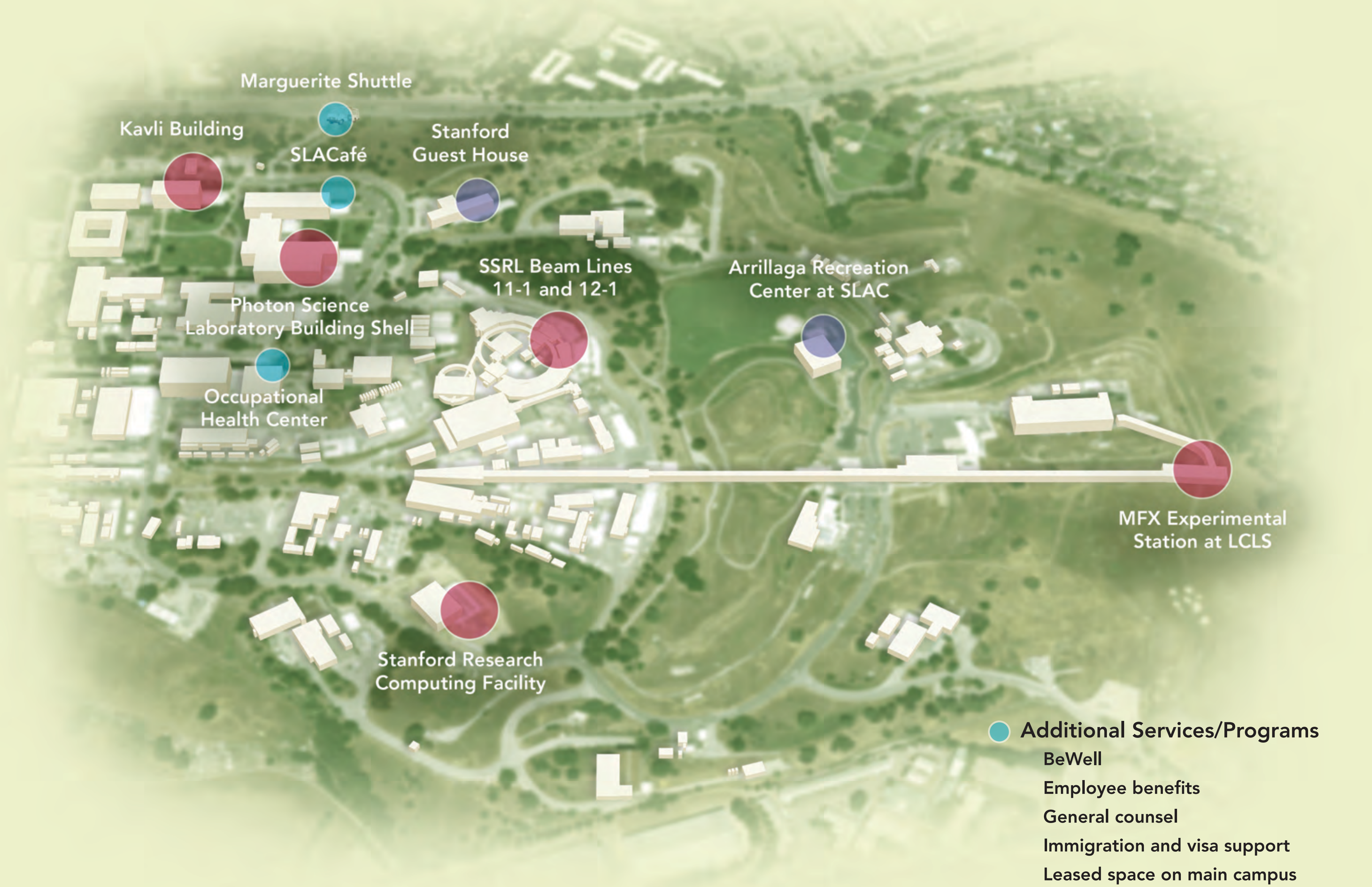
- Arrillaga Recreation Center at SLAC
- Kavli Building
- *Macromolecular Femtosecond (X-ray) Crystallography experimental station at LCLS
- Photon Science Laboratory Building shell
- *SSRL Beam Lines 11-1 & 12-1
- Stanford Guest House
- Stanford Research Computing Facility

**Partial Stanford funding*

### Services/Programs Provided by Stanford:

- BeWell
- Employee benefits
- General counsel
- Immigration and visa support
- Leased space on main campus
- Marguerite shuttle
- Occupational Health Center
- Office of Sponsored Research
- Payroll
- SLACafé

# Stanford Contributions



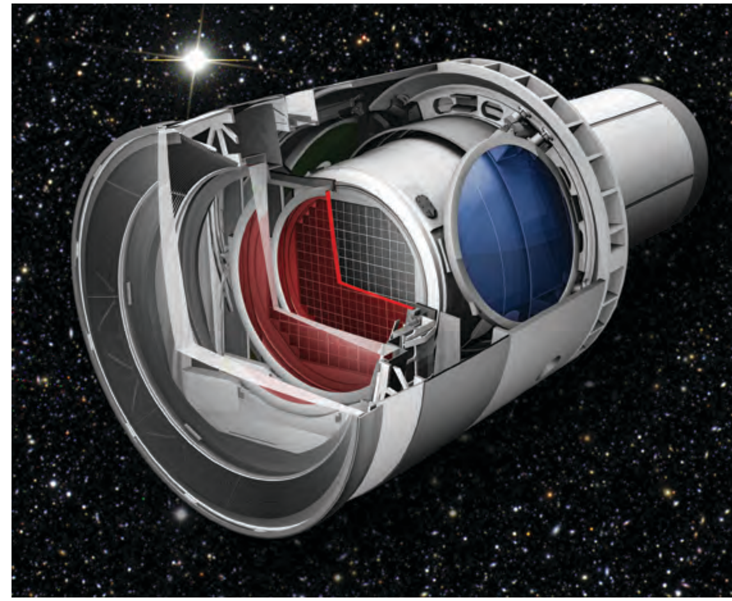

**Additional Services/Programs**
- BeWell
- Employee benefits
- General counsel
- Immigration and visa support
- Leased space on main campus
- Office of Sponsored Research
- Payroll

Services/Programs — General Facilities — Scientific Facilities

# SLAC+Stanford Initiatives

## World's Biggest Camera for LSST (SLAC+KIPAC)

SLAC is leading the assembly of the world's largest digital camera for the Large Synoptic Survey Telescope, a DOE/NSF-funded project that will survey the entire visible southern sky every few days from a mountaintop in Chile starting in 2022. The project's vast public archive of data will help researchers study the formation of galaxies, track potentially hazardous asteroids, observe exploding stars and better understand dark matter and dark energy.



## Smart Grid (SLAC+Civil and Environmental Engineering, Electrical Engineering, Precourt Institute)

A new applied research program will develop ways to collect data from power systems and from devices that are connected to the electrical grid, and use that combined data to better manage and operate grid systems as they incorporate increasing numbers of renewable energy sources. Work at SLAC and Stanford is being funded with a three-year, $4 million grant from the DOE Office of Energy Efficiency and Renewable Energy; SLAC is setting up a smart grid group and a lab in Building 24.

## Hydraulic Fracturing Under a Microscope (SLAC+School of Earth, Energy and Environmental Sciences)

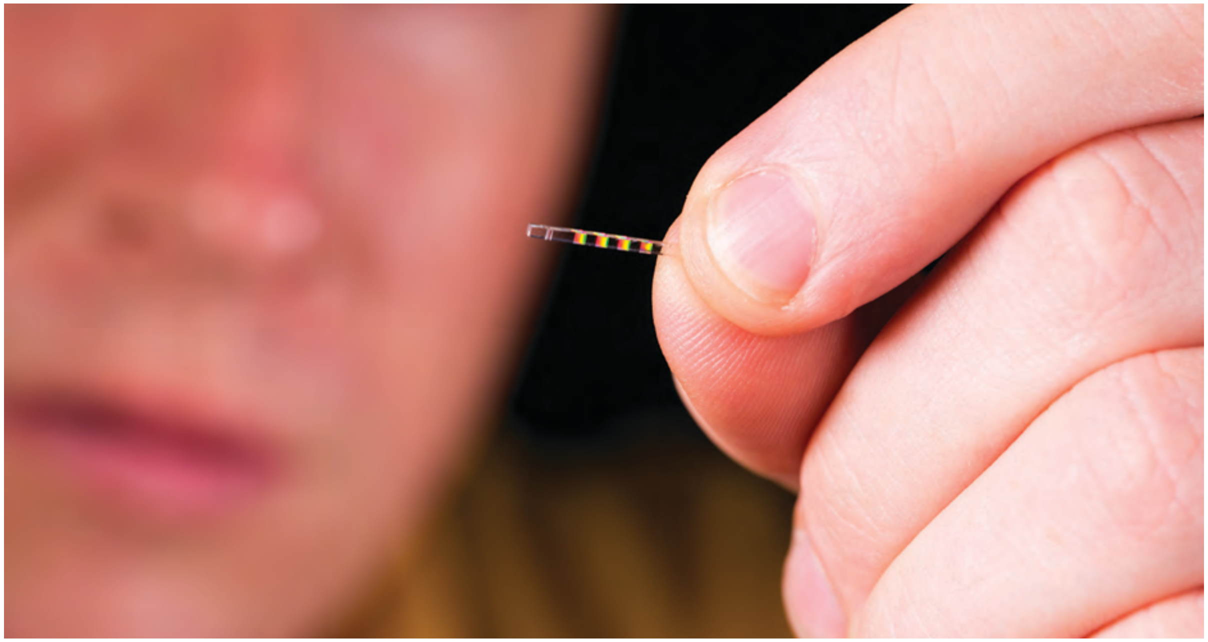
With funding from the National Energy Technology Laboratory and a Laboratory Directed R&D grant, a SLAC-Stanford team is using SSRL to study how chemicals used in hydraulic fracturing, or fracking, interact with shale to form precipitates that can clog pores, ultimately shutting down natural gas production. They're also investigating how contaminants such as uranium and radium are released from the rock. With SSRL they can examine pore structure down to very small scales and analyze the chemical composition of precipitates and contaminants.

## Battery Research (SLAC+SIMES, Materials Science & Engineering, Chemical Engineering)

SLAC and Stanford researchers are working to develop next-generation battery technologies, from high-capacity silicon anodes and sulfur cathodes to flexible batteries, flow batteries and self-healing electrodes. Some of these studies use SSRL to analyze battery and fuel cell materials during operation and find clues to improving their performance. Funding comes from several DOE programs and SLAC's Laboratory Directed R&D program.

## Fuels from $CO_2$ (SLAC+SUNCAT)

SLAC and Stanford researchers are searching for ways to convert carbon dioxide from burning fossil fuels into sustainable fuels or chemical feed stock. This would turn a global warming source into a global warming solution. SUNCAT is expanding its theoretical and experimental work in this area with a five-year, $7.5 million grant from the DOE's Joint Center for Artificial Photosynthesis and additional seed funding from SLAC.



## Accelerator on a Chip (SLAC+Applied Physics)

The Gordon and Betty Moore Foundation has awarded $13.5 million to Stanford for an international effort, including key contributions from SLAC, to build a working particle accelerator the size of a shoebox based on an innovative technology known as "accelerator on a chip." This novel technique, which uses laser light to propel electrons through a series of artfully crafted chips, has the potential to revolutionize science, medicine and other fields by dramatically shrinking the size and cost of particle accelerators.

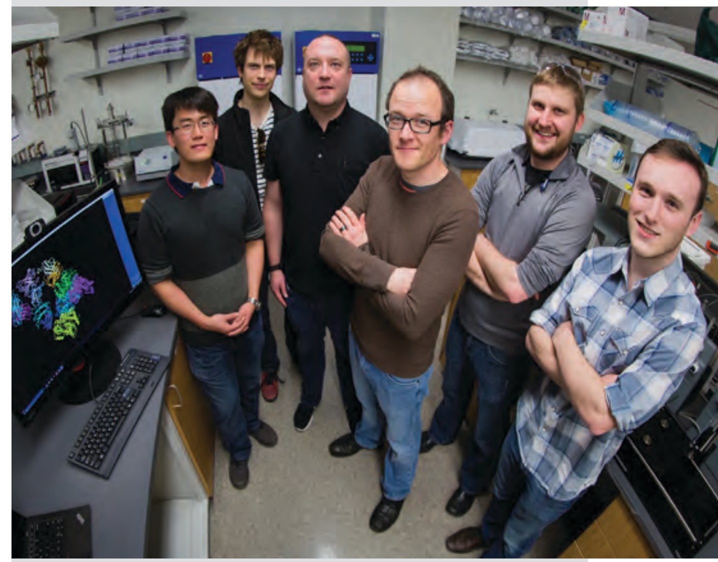
## Ultrafast Electron Diffraction (SLAC+PULSE)

The new UED "electron camera" at SLAC captures some of nature's speediest processes, revealing trillionth-of-a-second motions of electrons and atomic nuclei. UED complements SLAC's LCLS X-ray laser: While X-rays and highly energetic electrons both take snapshots of the interiors of materials, they "see" different things. Combining the two creates a more complete picture of ultrafast processes in complex systems such as magnetic data storage devices and chemical reactions.

## Two New Ways to Get Help From SLAC Experts

**Macromolecular Structure Knowledge Center (SLAC+ChEM-H, School of Engineering)**

This lab on the main campus provides state-of-the art equipment and expert help to faculty and students interested in growing, purifying and crystallizing proteins and other large biological molecules for study at SLAC's X-ray user facilities, SSRL and LCLS. In its first six months of operation, research groups from Medicine, Bioengineering, Chemical Engineering, Pathology, Chemistry and other departments took advantage of these services, which augment expert help available at SLAC X-ray facilities.



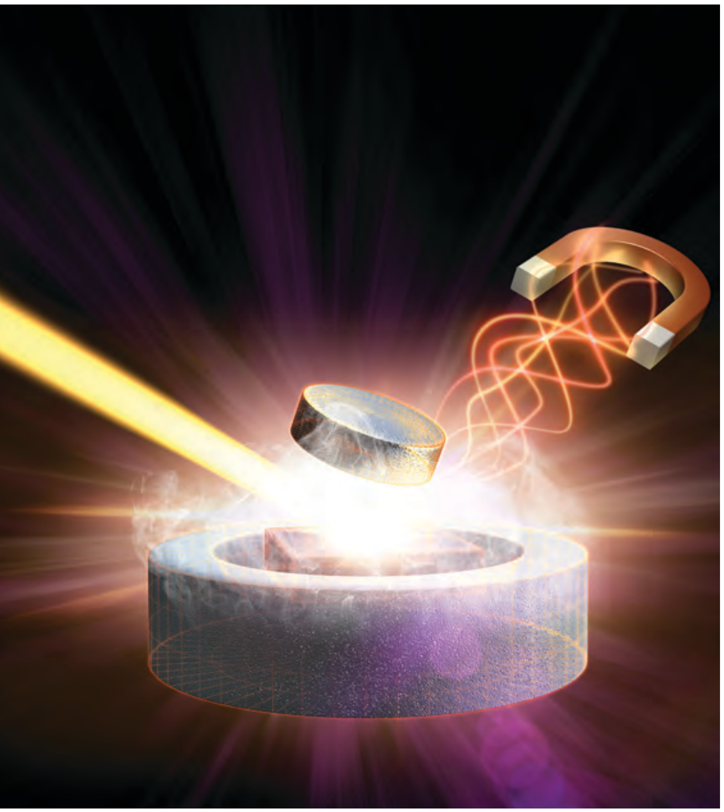
**System Prototyping Lab (SLAC+School of Engineering)**

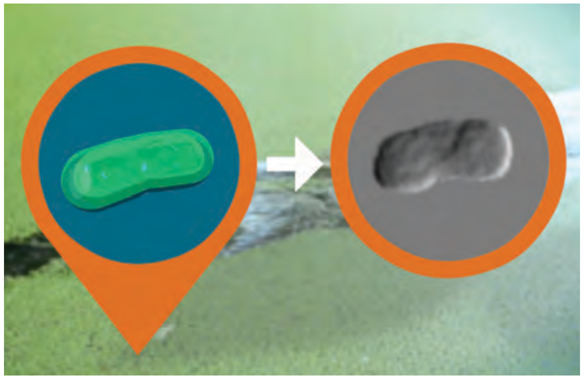
Part of the Paul G. Allen Building on the main campus is being reconfigured as a small facility where Stanford researchers can get help from SLAC experts with designing instrumentation, integrated circuits, electronics, sensors and so on. Construction is scheduled to finish in summer 2016.

# Recent Research Highlights

## First X-ray Portraits of Living Bacteria (LCLS)

An international team used the LCLS to capture the first X-ray portraits of living bacteria – cyanobacteria, or blue-green algae, which play a key role in Earth's oxygen, carbon and nitrogen cycles. Diffraction patterns produced by hitting live cyanobacteria with X-ray laser pulses were used to reconstruct 2-D images; 3-D images may also be possible in some cases. This result is a step toward possible X-ray explorations of the molecular machinery at work in viral infections, cell division, photosynthesis and other processes important to biology, human health and the environment.





## A New Dimension in High-temperature Superconductivity (LCLS, SSRL, SIMES)

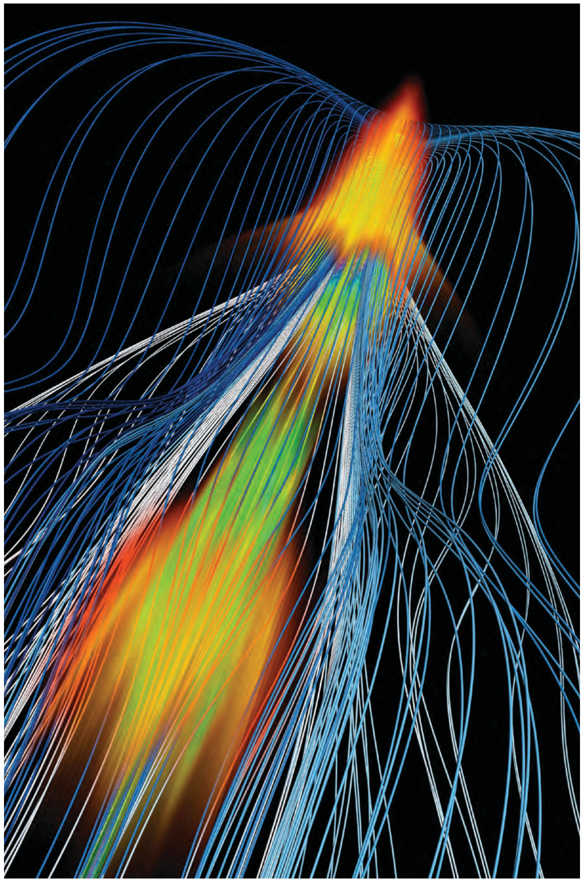
Experiments at LCLS revealed a new, 3-D type of "charge density wave" – a static, ordered arrangement of clumps of electrons – that coexists with superconductivity in yttrium barium copper oxide, or YBCO. It was a significant and unexpected twist in the 30-year quest to understand how high-temperature superconductors conduct electricity with no resistance at temperatures well above those of conventional superconductors. Important preparatory experiments were carried out at SSRL.

## Molecular Movie Reveals Ultrafast Chemistry in Action (LCLS)

Scientists for the first time tracked ultrafast structural changes in ring-shaped gas molecules as they burst open and unraveled. They compiled the full sequence of steps into computer animations to create a "molecular movie" of the changes, which took place in quadrillionths of a second. This pioneering LCLS study marked an important milestone in precisely tracking how gas-phase molecules transform during chemical reactions.

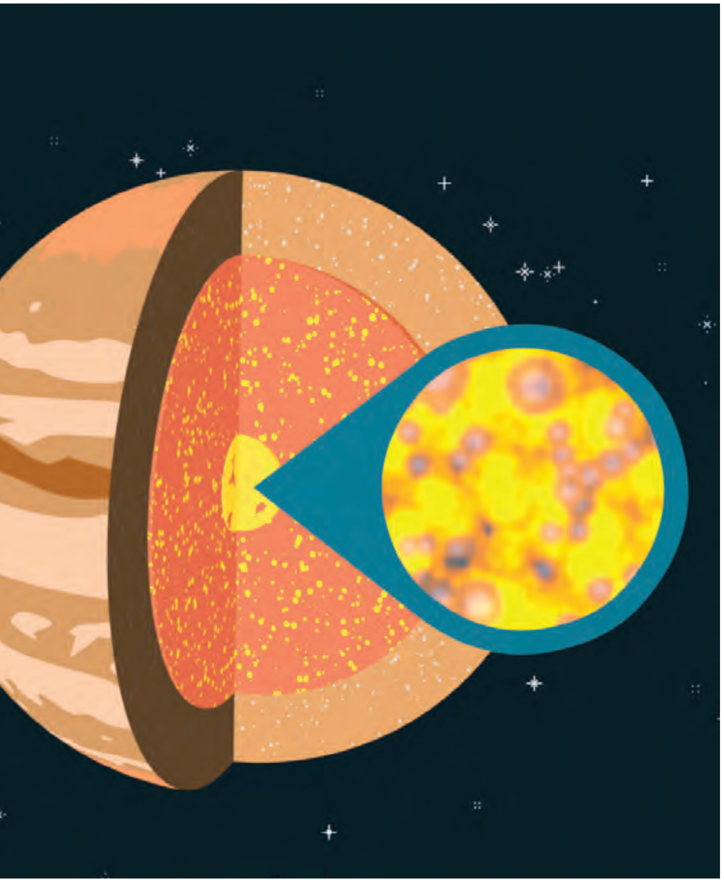
## Antimatter Catches a Wave (FACET)

Studies at SLAC's FACET user facility demonstrated a new, efficient way to accelerate positrons, the antimatter opposites of electrons, by having them "surf" waves of hot, ionized gas in a technique known as plasma wakefield acceleration. The method may help boost the energy and shrink the size of future linear particle colliders that probe nature's fundamental building blocks.



## Best Look Yet at Warm Dense Matter (LCLS)

A SLAC-led team used laser light to compress aluminum foil to a pressure more than 4,500 times higher than the deepest ocean depths and superheat it to 20,000 kelvins – about four times hotter than the surface of the sun. They used LCLS X-ray laser pulses to precisely measure the foil's properties as it transformed into warm dense matter – a state of matter found at the cores of giant planets – and then into a plasma. These studies of "extreme matter" offer insights into astrophysical processes and could also lead to a greater understanding of how to produce and control nuclear fusion as an energy source.

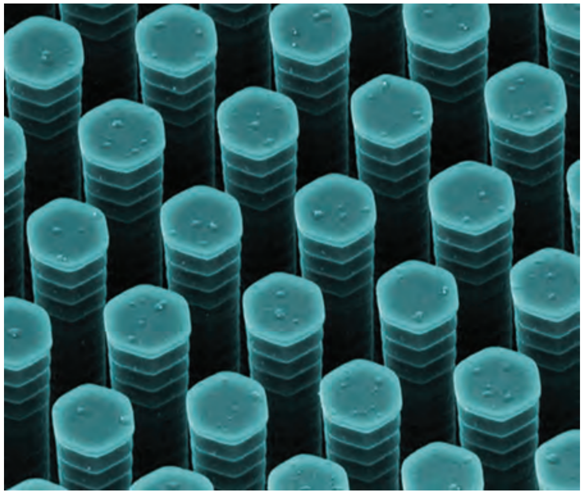


## Microscopic Rake Doubles Efficiency of Low-Cost Solar Cells (SIMES, SSRL)

SLAC and Stanford researchers developed a manufacturing technique that could double the electricity output of inexpensive solar cells by using a microscopic rake when applying light-harvesting polymers. The results give manufacturers a rational approach to improving their processes, and should be broadly applicable to making other polymer devices. The method was earlier used to improve the conductivity of organic semiconductors. The team used SSRL X-rays to measure the effects of the raking and fine-tune the process.

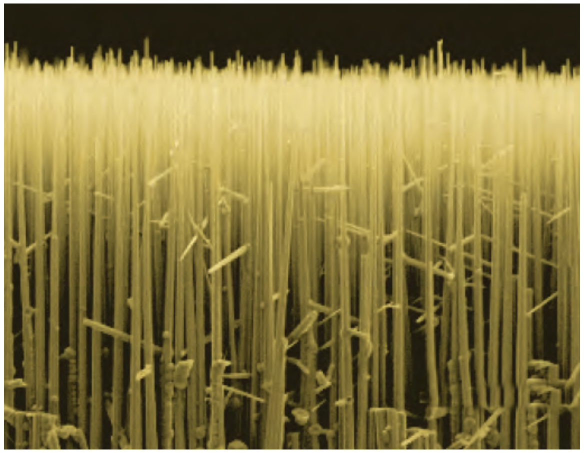
## Searching for Dark Matter in Rare Dwarf Galaxies (SLAC+KIPAC)

Dwarf galaxies, which hold just a few hundred stars, should be good places to hunt for dark matter: Any gamma rays they emit should be from dark matter annihilation. KIPAC scientists were on a team that used the Dark Energy Survey (DES) to discover eight new potential dwarf galaxies orbiting the Milky Way in 2015. They also took part in two independent searches for gamma rays coming out of dwarf galaxies using the Large Area Telescope (LAT), a SLAC-assembled instrument aboard NASA's orbiting Fermi Gamma-ray Space Telescope. The LAT searches came up empty-handed; still, the results were important because they help put limitations on the properties that hypothetical dark matter particles can have.



## Diamondoid Tips Give Electron Guns More Oomph (SIMES)

Electron guns are workhorse tools for research and industry. SIMES researchers figured out how to increase their electron emissions 13,000-fold by applying a single layer of diamondoids – tiny, perfect diamond cages – to a gun's sharp gold tip. SLAC and Stanford are the world's leading center for diamondoid research. These latest results suggest a new approach for increasing the power of electron guns, and provide an avenue for designing other types of electron emitters with atom-by-atom precision.



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The 426-acre campus of SLAC National Accelerator Laboratory is located in Silicon Valley, 30 miles southeast of San Francisco, Calif., on the Stanford University campus.

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**On the Cover:**

SLAC's new Science and User Support Building, with Stanford's Hoover Tower in background at left.

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