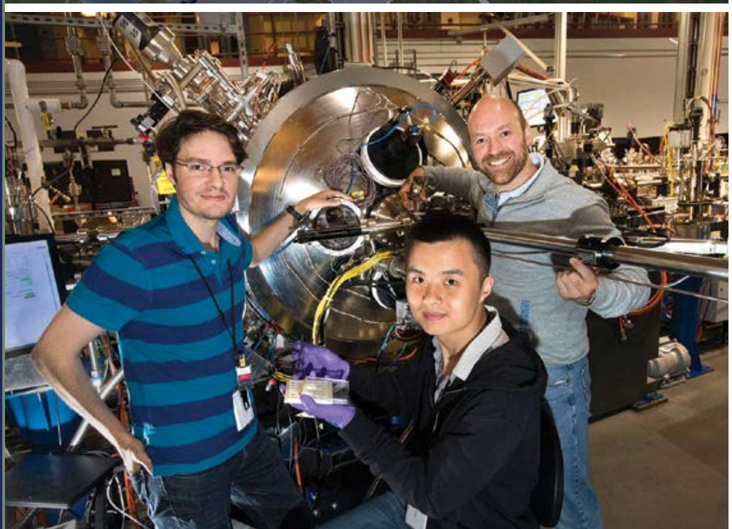
SHARED RESEARCH FACILITIES

A Key Source of U.S. Scientific and Industrial Leadership

In the aftermath of World War II, DOE and its predecessors built nuclear reactors used as research tools by nuclear engineers and high energy electron accelerators used by physicists to study the properties of sub-atomic particles. Before long, however, other scientists began to think of ways to use these facilities to study ordinary materials: tapping the neutrons produced in a reactor core or manipulating electron beams to create intense X-rays. Soon a few scientists gained permission to "borrow" access to these facilities and extract beams of neutrons or X-rays to interact with the materials they wanted to study. The results were spectacular. It rapidly became clear that such probes could provide insights into the detailed physical and electronic structure of materials that were not obtainable in any other way—including materials essential for national security as well as those used in all forms of energy production.

Electrons accelerated to almost the speed of light by a linear accelerator are then run through a gauntlet of magnets (shown here) that force the electrons to zigzag violently and give off extremely intense X-ray pulses that are used to study material properties and other phenomena. *(SLAC National Accelerator Laboratory)*



Top: Aerial view illustrates the enormous scale of Brookhaven National Laboratory's X-ray source, which replaced the original (smaller and less powerful) X-ray facility, part of BES's continuing stewardship of its shared research facilities. Electrons circulating at high speed in the circular magnetic storage ring are converted into intense X-rays for research use at dozens of individual beamlines. *(Brookhaven National Laboratory)*

Bottom: Visiting scientists at Brookhaven National Laboratory's X-ray source install their equipment on an X-ray beamline specialized for "soft" X-rays appropriate for studying a material's magnetic properties. *(Brookhaven National Laboratory)*

It was also clear that the cost and scale of such facilities were beyond the reach of individual scientists or even of major universities. So 40 years ago DOE's Basic Energy Sciences (BES) office began to build dedicated national X-ray and neutron facilities that could be used—"shared"—by many researchers. The first such facility, located at Brookhaven National Laboratory on Long Island, produced X-rays of unparalleled intensity along with the ability to focus them narrowly, enabling researchers to "see" very deeply into a material. The scale of the facility—about the size of a football field—enabled dozens of individual beamlines that extracted X-rays for experiments and could be adapted to individual needs. These capabilities attracted a remarkable array of scientific talent, both senior researchers from leading industrial labs such as Bell Labs and IBM and a large crop of bright, ambitious young scientists from universities. Several large industrial companies, paying their own way, also used the facility or even sponsored their own beamlines.

Major discoveries came rapidly, but that was not the only achievement. The camaraderie of the scientists working on the many beamlines began with sharing tools and beer, but soon led to sharing scientific advice and to a culture of collaboration that accelerated the research. In effect, shared research facilities came to mean not only shared access to unique research tools, but also shared effort and advice among the users, the scientific staff of the facility, and the staff of the National Laboratory where the facility is located.

The culture of cooperation began at Brookhaven, but spread as BES built additional X-ray sources, two different types of neutron sources, and a couple of decades later shared nanoscale research centers, which have special spaces where materials can be kept at the level of cleanliness nanoscience requires, fabrication tools, and advanced electron microscopes. These unique national facilities, located at DOE National Laboratories in California, New Mexico, Illinois, Tennessee, and New York, have helped transform science—enabling unprecedented insights into the structure of materials and the nature of chemical and biological processes. They have enabled U.S. university-based scientists to become extremely productive and even global leaders—recognized by four Nobel Prizes for work that utilized shared research facilities.

Equally important, these shared research facilities have helped transform nuclear weapons security and many areas of the U.S. economy—from automotive engines to pharmaceuticals and petrochemicals, and from semiconductors to steel and other structural metals. They have catalyzed newer fields such as nanotechnology. Today these facilities play a critical role in industry-led efforts to create advanced batteries for electric cars and new vaccines to combat public health threats such as the Zika virus, as well as helping to provide a foundation for quantum computing. It is not an exaggeration to say that these shared facilities and the culture of cooperation they engender, guided and supported by BES, have played a major role in U.S. economic prosperity for the past 40 years and continue to do so.

This BES-supported ecosystem of shared research facilities now includes five X-ray sources (each specialized for solving different kinds of problems), five nanoscale research centers, and two different types of neutron sources. One measure of the success of these facilities is the volume of users, which in FY 2017 included nearly 16,000 separate researchers from universities, national laboratories, and industry. But the demand for access to these facilities—which is free for non-commercial users but subject to competitive application—exceeds their capacity: at the neutron sources, for example, only one-third of some 9,000 applications last year could be accommodated. BES has regularly upgraded these facilities, both to add capacity or meet evolving user needs and to take advantage of advanced technology—in particular, for X-ray sources and one kind of neutron source, technology developed with major input from accelerator scientists supported by DOE's High Energy Physics office. An ongoing upgrade to the X-ray source at Argonne National Laboratory near Chicago will increase its effectiveness 500-fold; an upgrade planned for one of the neutron sources at Oak Ridge National Laboratory will double its user capacity.

Most of the scientists sharing these facilities in 2017—68 percent—came from universities, 25 percent came from government laboratories, and about 7 percent from industry or other institutions. Industry users pay their own way if the research is proprietary, and the technological and economic impact of their research is greater than the number of users might suggest. That's because industry typically uses these facilities for applied research—

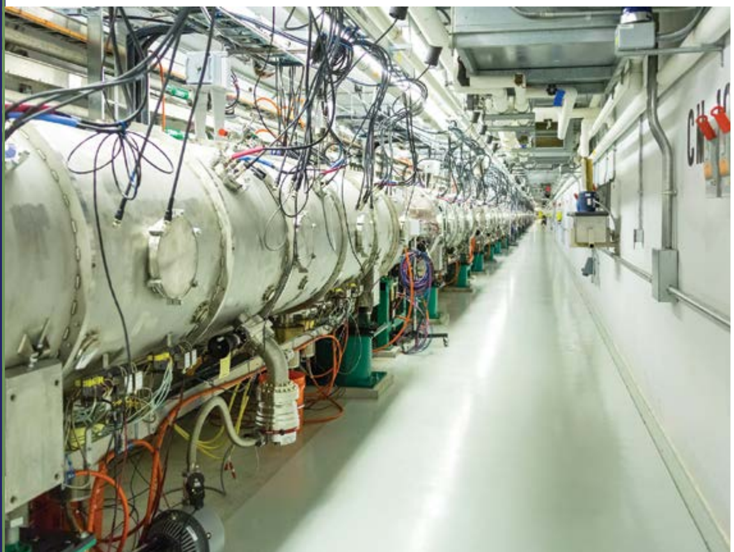
Graduate students (prospective future scientists) learning the characteristics of the X-ray source at Argonne National Laboratory and how to use it for a variety of scientific studies. DOE's Basic Energy Sciences office supports these instructional efforts and similar ones at Oak Ridge National Laboratory's neutron sources to help stoke the U.S. pipeline of scientific talent. *(Argonne National Laboratory)*

fine-tuning drug candidates or engine designs or metallic alloy compositions, as opposed to exploratory fundamental research. Consortia of pharmaceutical companies have built and maintain dedicated beamlines at one of the X-ray sources, and some major energy and industrial companies regularly reserve time at both X-ray and neutron sources.

The shared research facilities serve an educational role as well. Nearly 40 percent of the academic users are graduate or advanced undergraduate students, working as part of a professor's scientific team and getting an unparalleled exposure to cutting edge research. These facilities thus play an important role in developing the future scientific workforce.

Overwhelmingly, however, the rationale for the continuing investment in shared research facilities is their utility in advancing knowledge and enabling improved technology. Highlights of the facilities and their impact include:

> **Shared neutron research facilities.** Both neutron sources are located at DOE's Oak Ridge National Laboratory. One consists of a nuclear reactor that produces multiple beams of low-energy neutrons that are especially useful for examining nano-scale materials and biological molecules. The reactor is also used to produce radioactive medical isotopes, including one that was recently approved to treat prostate cancer. A second neutron source is powered by an accelerator



Top: Protons accelerated by this underground linear accelerator at Oak Ridge National Laboratory are collided with a mercury target, generating high-energy pulses of neutrons that are directed into multiple beamlines for research into the properties of materials. *(Genevieve Martin / Oak Ridge National Laboratory)*

Bottom: Columbia University researchers using a beamline from the neutron source at Oak Ridge National Laboratory to analyze a suspension bridge cable and how it might fail under stress, in order to facilitate design of better cables. *(Genevieve Martin / Oak Ridge National Laboratory)*

that smashes high-energy protons into liquid metal targets to generate intense pulses of high-energy neutrons, a technique pioneered earlier with BES support at Argonne National Laboratory. The Oak Ridge pulsed neutron source feeds 19 different beamlines and, for the last decade, has been by far the most powerful neutron source in the world.

Neutrons are used both to identify the location of atoms within a material and to study how they move. Because neutrons are tiny magnets, they are also uniquely useful in studying magnetic properties. Because of their penetrating power, pulsed neutron beams have been used by auto companies to look inside an operating gasoline engine and confirm the stability of its aluminum alloy; they have also been used to analyze the stress and strain of bridge cables. Neutrons also turn out to be ideal to study the behavior of light elements such as the lithium ions in batteries, leading to significant improvements in battery performance.

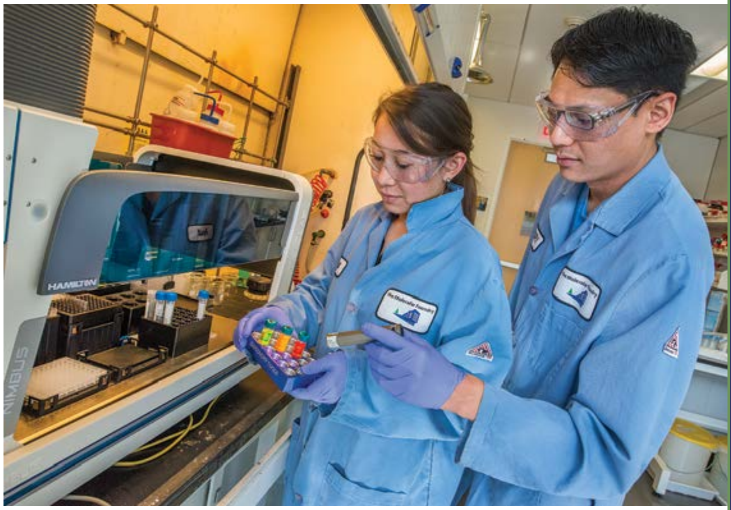
> **Shared X-ray research facilities.** The five BES-supported facilities are located at National Laboratories in California, Illinois, and New York. The facilities are immense, because they accelerate electrons close to the speed of light and, in most facilities, store them in a magnetic ring large enough to encircle a football stadium, before converting them to intense beams of X-rays. Like X-rays in a dentist's office, but a billion times more intense, the X-ray sources enable scientists to probe both the structure and the electronic properties of matter.

The X-ray sources are the most heavily used of the BES shared research facilities, reflecting their versatility. For more than two decades, the nation's chip manufacturers have used them repeatedly to improve the tools for semiconductor circuit manufacturing at ever-smaller dimensions—research initially funded by a DOD research agency and then by an industry consortium. X-ray sources have been used to study and help improve lithium ion batteries and metal-oxide catalysts that can facilitate production of fuels and petrochemicals. The X-ray pulses are so fast they can "freeze" the motion of the fuel being injected into an automotive engine at 1,500 feet per second, enabling engineers to optimize injector designs that have improved engine efficiency and reduced emissions.

The X-ray sources have also become an essential tool for biomedical science—a development that was not anticipated—because they enable both university scientists and pharma companies to analyze and understand the structure of complex biological molecules. The outcome has been transformative, resulting in four Nobel Prizes and in the development of the majority of drug candidates now undergoing clinical trials. Recent results include new drugs for leukemia, melanoma, and diabetes, as well as a new vaccine for the deadly Lassa virus that infects hundreds of thousands of West Africans very year.

> **Shared nanoscale research facilities.** Fully deployed only in the last decade, there are five centers located in California, New Mexico, Illinois, Tennessee, and New York. They provide users not only with nanoscale fabrication facilities and analytical tools, but also expert staff that can collaborate with researchers. That has enabled university scientists from many fields to engage in nanoscience, resulting in numerous breakthroughs in nanomaterials and discovery of new quantum phenomena. This collaboration model also led to the development—by university scientists at Berkeley and the nanoscale research centers—of advanced electron microscopes capable of "seeing" matter at subatomic scales.

Among the recent discoveries enabled by the nanoscale centers is a material using nanoparticles that can quickly absorb and release hydrogen, making it a potential storage technology for hydrogen fuel, a key step towards making fuel-cell cars a commercial reality. Researchers have also used a nanotech approach to invent a sponge that can absorb 90 times its weight in oil from water—and thus could greatly improve cleanup of oil spills. Still another promising nanotechnology is a self-healing diamond-like carbon coating for metals that is essentially frictionless—and could revolutionize lubrication and reduce wear in car engines and giant wind turbines.



Scientists prepare nanoparticle samples for analysis at a Nanoscale Science Research Center in California.
(Lawrence Berkeley National Laboratory)

Shared research facilities on the scale described here are a U.S. invention, but there is growing competition from Europe—which has some even more advanced X-ray sources and is building an advanced neutron source—and from China. What remains unique about the BES facilities, however, is that they are located at DOE national laboratories, enabling a close coupling among scientists from the laboratories, the scientific staff of the facilities, and the visiting scientists who use the research tools. That, and the broader culture of sharing and cooperation among scientists working on similar problems—facilitated by long-term BES support—remains a unique U.S. advantage.