

## **Accelerator and Detector Research**

### **Portfolio Description**

This activity supports basic research in accelerator physics, x-ray and neutron detectors, and advanced x-ray optics instrumentation. Accelerator research is the cornerstone for the development of new technologies that will improve the performance of light sources and neutron spallation facilities. The research explores new areas of science and technologies that will facilitate the construction of next-generation accelerator-based user facilities. The program is investing in research leading to a new and more efficient generation of photon and neutron detectors and in x-ray optics which are crucial components in the optimal utilization of the neutron or photon beams. Research includes studies on creating, manipulating, transporting, and diagnosing ultra-high-brightness electron beam behavior from its origin at a photocathode to propagation through undulators, and on transporting, analyzing, and detecting x-ray beams. Studies on achieving sub-femtosecond free-electron laser (FEL) pulses are also undertaken. Demonstration experiments are being pursued in advanced FEL seeding techniques, the study of methods to control the spectral properties of an x-ray self-amplified spontaneous emission (SASE) FEL using amplitude and phase mixing, and other optical manipulations to reduce the cost and complexity of seeding harmonic generation FELs. High-precision timing techniques for synchronization of accelerator and laser systems and for high-resolution measurements of electron- and photon-beam pulse duration and timing are being explored. Experimental tests of beam phase-space distributions are being conducted to demonstrate loss-control mechanisms for very high proton beam currents at neutron sources. Theoretical and experimental studies on collective electron effects are also supported.

### **Scientific Challenges**

The Accelerator and Detector Research Program supports work toward the development of:

- New accelerator concepts crucial to the design and upgrade of synchrotron light sources and neutron scattering facilities.
- High-repetition-rate, ultra-bright, transform-limited, femtosecond x-ray pulses over a broad photon energy range with full spatial and temporal coherence.
- New electron sources to optimize the performance of FEL facilities, which are presently limited in x-ray power and spectrum coverage due to the unavailability of suitable injectors. Ultra-fast and ultra-bright electron sources are also required for advances in ultrafast electron diffraction and future ultrafast electron microscopy.
- Components suitable for diffraction-limited storage rings with beamlines, optics, and detectors compatible with the increase in brightness afforded by upgraded storage rings.
- New detectors that are capable of using the high data rates associated with high-brightness sources, thus increasing beamline efficiencies and user throughput.
- Low-background, high-spatial-resolution neutron detectors, and replacement of Helium-3-based detectors.
- X-ray optics instrumentation that can compensate for detector limitations to enhance the combined spatial, temporal, and energy resolution of experimental data.
- Special emphasis on R&D leading to more energy-efficient machines and devices that go beyond the most common methods of particle acceleration.

### **Projected Evolution**

X-ray and neutron scattering will continue to play a central role in the growth of Basic Energy Sciences (BES) programmatic science. The Spallation Neutron Source (SNS) will be the most

powerful neutron spallation source in the world for years to come. Future FEL light sources are expected to provide high-repetition-rate, ultra-bright, transform-limited, femtosecond x-ray pulses over a broad photon energy range, with full spatial and temporal coherence.

Two major components will be required for the advancement of material science: the production of photon beams with increased average flux and brightness, and the detection tools capable of responding to the high photon-beam intensity. The first component will require higher repetition-rate photocathode guns and radiofrequency systems, and photon beams of enhanced temporal coherence, such as produced by improved seeding techniques or x-ray oscillators in the case of FELs. Secondly, detectors will require higher computational capabilities per pixel, improved readout rates, radiation hardness, and better energy and temporal resolutions. Additionally, R&D will be required to produce ultrafast beam instrumentation capable of measuring accurately femto- and attosecond bunch lengths. Higher neutron-flux capabilities at the SNS will demand high-intensity hydrogen negative ion currents, possibly provided by the development of high-power and high-frequency lasers, and detectors designed for advanced neutron imaging with very high throughput. Finally, R&D emphasizing energy-efficient machines and strong collaborations among the national laboratories and universities will allow a cost-effective, coordinated, and interdisciplinary approach to research and development in accelerators, detectors, and x-ray instrumentation.

### **Significant Accomplishments**

- This activity was a major supporter of theoretical and experimental studies that led to realization of the Linac Coherent Light Source (LCLS). Theoretical and simulation studies addressed many of the fundamental physics questions concerning SASE FELs and high-brightness beams, leading to successful experiments.
- A novel concept to generate multiple simultaneous spikes, or multi-color, x-ray FEL pulses with unprecedented performance in terms of power and pulse-delay control was demonstrated. The novel scheme outperforms existing techniques at soft x-ray wavelengths, and produces high-power, femtosecond pulses flexible color separation. The development opens the way to new forms of spectroscopy.
- An innovative *in situ* and *in operando* x-ray analysis system was developed to fully explore and analyze the physics and chemistry of photo-cathode materials.
- A program that explores the application of 3D techniques to the difficult problem of integrating x-ray sensors of high-resistivity silicon and readout application-specific integrated circuits of low-resistivity silicon has achieved the first successful three-dimensionally integrated chip for photon science. When fully developed, these sensors will be capable of handling synchrotron radiation at energies up to 100 keV.
- A new imaging pixel array detector was developed that can acquire successive high-dynamic-range x-ray images at rates of up to 10 million frames per second, allowing acquisitions of real-time x-ray “movies” of structural changes in matter.
- A tool that provides a powerful pulse-by-pulse diagnostic with femtosecond resolution allows scientists to directly measure the x-ray power profile and to obtain a much more detailed view of the individual pulses that interact with their samples. For the first time, scientists can directly measure the x-ray power profile on a shot-by-shot basis with femtosecond resolution, providing a noninvasive diagnostic tool for photon experiments and new insight into lasing dynamic.
- A suite of tools for analysis and management of scattering data obtained in materials experiments at BES facilities was developed. This collaboration with the Office of Advanced Scientific Computing Research was driven by the increasing data and

computational requirements of handling and using data in diffuse scattering analysis of materials and their structural characterization.

- An ultrafast electron diffraction system developed to complement the capabilities of x-ray FELs has achieved unprecedented detection sensitivities and has demonstrated the highest combined spatial and temporal resolutions of similar existing systems. The system was used to detect the temporal evolution of non-equilibrium phonons in femtosecond laser-excited ultrathin single-crystalline gold films, establishing the usefulness of high-energy UED for dynamic momentum resolved phonon studies.

### **Unique Aspects**

Technological advances require new materials and chemical processes for novel and improved sources of energy. The necessary tools enabling control and observation of the temporal evolution of electrons, atoms, and chemical reactions demand machines capable of producing high brightness, high duty factor, and short beam pulses. The accelerator and detector research carried out by the program aims to improve the output and capabilities of synchrotron radiation light sources and the neutron scattering experiments at facilities that are the most advanced of their kind in the world. These light sources and neutron scattering sources represent the largest collection of such facilities operated by a single organization in the world.

### **Mission Relevance**

The Accelerator and Detector Research program supports the most fundamental of research needs to characterize and control materials at the atomic and molecular level. In order to understand, predict, and ultimately control materials properties, it is necessary to determine the atomic constituents of materials, the positions of the atoms in materials, and how the materials behave under the influence of external perturbations such as temperature, pressure, chemical attack, and excitation by photons, electrons, and other particles. The activity seeks to develop new concepts in accelerator science to be used in the design of accelerator facilities for synchrotron radiation and spallation neutron sources that will provide the means necessary to achieve a fundamental understanding of the behavior of materials. Also supported is the development of higher-precision, more efficient detectors capable of acquiring data several orders of magnitude faster than state-of-the-art detectors, and advanced x-ray optics that offers higher precision and higher accuracy in order to fully exploit the high fluxes delivered by the new facilities.

### **Relationship to Other Programs**

- This activity has very strong interactions with all BES programmatic research that uses synchrotron and neutron sources. This includes research in atomic physics, condensed matter and materials physics, chemical dynamics, catalysis, geosciences, high-pressure science, environmental sciences, engineering, biosciences, and much more.
- This activity is a stakeholder of the Office of High Energy Physics Accelerator Stewardship subprogram, established to support use-inspired basic research in accelerator science and technology.
- There is an ongoing collaboration with the Advanced Scientific Computing Research program to support code development relevant to beam dynamics and to develop tools and codes addressing the exponential growth of experimental data at the BES facilities.
- This activity also interacts with other DOE offices, especially in the funding of capabilities whose cost and complexity require shared support.
- There are ongoing industrial interactions through the DOE Small Business Innovation Research and Small Business Technology Transfer programs for the development of advanced accelerator technology, detectors, and x-ray optics instrumentation.