Accelerator Technology for the Nation

Summary

Accelerators underpin every activity of the Office of Science and, increasingly, of the entire scientific enterprise. From biology to medicine, from materials to metallurgy, from elementary particles to the cosmos, accelerators provide the microscopic information that forms the basis for scientific understanding and applications. The combination of ground and satellite based observatories and particle accelerators will advance our understanding of our world, our galaxy, our universe, and ourselves.

Essentially all we know today and will learn in the future about the fundamental nature of matter is derived from probing it with directed beams of particles such as electrons, protons, neutrons, heavy ions, and photons. The resulting ability to "see" the building blocks of matter has had an immense impact on society and our standard of living. Over the last century, particle accelerators have changed the way we look at nature and the universe we live in and have become an integral part of the Nation's technical infrastructure. Today, particle accelerators are essential tools of modern science and technology.

For example, about 10,000 cancer patients are treated every day in the United States with electron beams from linear accelerators. Accelerators produce short-lived radioisotopes that are used in over 10 million diagnostic medical procedures and 100 million laboratory tests every year in the United States. Nuclear diagnostic medicine and radiation therapy together save countless lives and generate about $20 billion in business annually. The use of ion beams from accelerators to embed doped layers in semiconductors is essential to the multi-billion-dollar semiconductor industry. Ion implantation is also used to harden surfaces such as those of artificial hip or knee joints, high-speed bearings, or cutting tools by using ion beams to alloy a thin surface layer. X-ray lithography with intense x-ray beams from synchrotron light sources etches microchips and other semiconductor devices. Accelerators are also used for accurate, nondestructive dating of archeological samples and art objects.

Ever since Ernest Rutherford discovered the atomic nucleus in 1911 by bombarding atoms with beams of alpha particles obtained from naturally radioactive sources, particle beams have been used to investigate the ultimate structure of matter. To probe more deeply into the structure of nuclei, we had to learn how to accelerate these particle beams by artificial means to higher and higher energies, and as we did so, we were able to penetrate even into the structure of neutrons and protons themselves. As a result, we discovered that neutrons and protons are composite systems of smaller particles called quarks. Indeed we have discovered a deeper level in the fundamental structure of matter, an advance comparable to the discovery of the atomic nucleus by Rutherford. This new world of quarks and leptons and the forces that affect them goes by the prosaic name of "The Standard Model," but it will stand as one of the lasting achievements of the twentieth century.

As experiments peer deeper and deeper into the heart of matter, they continue to open strange new subatomic worlds and striking new vistas on the cosmos. Possibilities of finding the source of mass, a new class of "supersymmetric" particles, and a quark-gluon plasma like that in the early universe invite us to probe even deeper. Astronomical observations suggest that the universe is filled with dark matter and dark energy unlike anything we have seen before. Particle accelerators hold the promise to shed light on these great mysteries. We are beginning to address in a systematic and scientific way the most profound human questions: "Where did we come from? Where are we going?"

The modern era of accelerators began in 1937 with E.O. Lawrence's first cyclotron, a circular machine six inches diameter, which you could hold in the palm of one hand, and today it includes accelerators with lengths on the scale of miles. It has progressed from accelerators that strike essentially stationary targets and must overcome their inertia, to accelerators with counter-rotating beams that collide head-on and make full use of the energy in the beams. It includes the B-Factory at the Stanford Linear Accelerator Center, in which electrons collide head-on with positrons, their anti-particles; the Fermilab Tevatron, the world's highest energy accelerator, which collides protons with anti-protons; the Relativistic Heavy Ion Collider at Brookhaven National Laboratory, which collides gold nuclei with each other; and the Large Hadron Collider, a proton-proton collider now under construction in Europe. These are among the grandest scientific instruments ever built.

Smaller-scale accelerators and synchrotron light sources, a direct outgrowth of modern accelerator technology, have had an enormous impact on the other physical sciences and the biological sciences. Accelerated electron beams produce secondary beams of x-rays that are used to study the structure of atoms and molecules, to probe the mysteries of superconductors, the properties of polymers, plastics, ceramics—essentially all industrially important material—to locate minute traces of elements within living cells, to determine the structure of proteins and to observe the means by which viruses attack cells. The Spallation Neutron Source, which is being constructed at Oak Ridge National Laboratory, will provide unparalleled neutron beams to probe the motions of atoms in matter and the magnetic properties of materials.

Particle accelerators are also an essential part of the Nation's technical infrastructure for health care, for industry and for national security. One third of the 15,000 accelerators in operation worldwide are used in radiotherapy and almost two-thirds are used for industrial applications such as semiconductor production, sterilization, and materials preparation or in processes such as x-ray micro-machining. Ultra-fast x-ray sources are being developed and used for nuclear stockpile stewardship, and accelerators are deployed for every day use in non-invasive x-ray inspection of cargo containers.

The Office of Science of the Department of Energy (DOE), like its predecessor agencies, has played the lead federal role in developing these powerful tools and in establishing national accelerator facilities for scientific research. Modern research accelerator facilities are often very large installations, highly specialized and open to thousands of researchers based in universities, industry, and national laboratories. About 15,000 specialists annually take advantage of the accelerator facilities that the Office of Science operates on behalf of the Nation.

Future opportunities for advancement in the physical and life sciences from accelerator-based research are enormous, but new and improved accelerator capabilities must be created to exploit them. Among Federal funding agencies, the DOE Office of Science is unique in its stewardship for the development and operation of these large user facilities. Part of this stewardship is supporting accelerator science to ensure that the needed accelerator R&D is performed and that skilled manpower is trained to provide next-generation facilities at the cutting-edge for the sciences that they serve.

Accelerator science is an interdisciplinary field spanning a range of technologies from applied superconductivity and microwave generation to high-performance computing. This is an area in which the Department of Energy is a recognized leader—bringing together diverse skills to tackle a problem that can only be solved by a multi-disciplinary approach. As we look to the future, we project a need for an initiative in accelerator research and development focusing on these critical areas.

- **Research at existing operating accelerators:** Achieving high operational performance and extending and improving the capabilities and research reach of existing accelerators. Provides immediate pay-off in terms of increased scientific productivity, enhancements in scientific research, and economy of operations.

- **Expanded collaborations:** Many of today's and tomorrow's accelerator projects are so large that more highly trained scientists and engineers are required. Collaboration between laboratories is an integral part of large projects such as the Spallation Neutron Source and the Large Hadron Collider (being built in Europe with significant U.S. and Asian participation) and must be further developed for future projects. This will address two critical needs. It maintains core competencies and a strong highly trained professional force and alleviates the transient peak needs of trained manpower at a given site.

- **Educational Opportunities:** The role of university faculty and students should be expanded in all aspects of accelerator research from operating accelerators to advanced accelerator research. This will allow the breadth of knowledge and expertise that resides at the universities to be brought to accelerator research, and young scientists will have the opportunity to learn and become tomorrow's leaders.

- **Advanced accelerator research:** There are technologies and areas of physics research that have the potential to qualitatively change the way we build accelerators. These advanced topics are at a formative stage and range from the application of widespread technologies such as lasers, to forward-looking concepts such as plasma-based accelerators. Research into these advanced concepts is critically important for the long-term viability of accelerator-based science. It is also leading-edge science in its own right and appeals to a broad spectrum of faculty, scientists and students who can bring diverse intellectual approaches to these challenging problems.

This Accelerator R&D initiative will be managed in a manner that recognizes the full spectrum of needs for the Nation. Accelerator R&D keyed to the needs of High Energy Physics, Nuclear Physics, Fusion Energy Sciences, Basic Energy Sciences, and Biological and Environmental Research will have important differences in emphasis. For example, the near and long term advancements needed for light sources and medical accelerators are different from those needed for the next generation of high energy and nuclear physics accelerators, and would benefit from specific efforts. The special research needs of the various critical fields need to be recognized in the context of a coordinated national accelerator effort. As in the past, that coordination and focus will come from the Department of Energy's Office of Science.

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