Probing the Structure of Matter

a history of accelerators at Los Alamos

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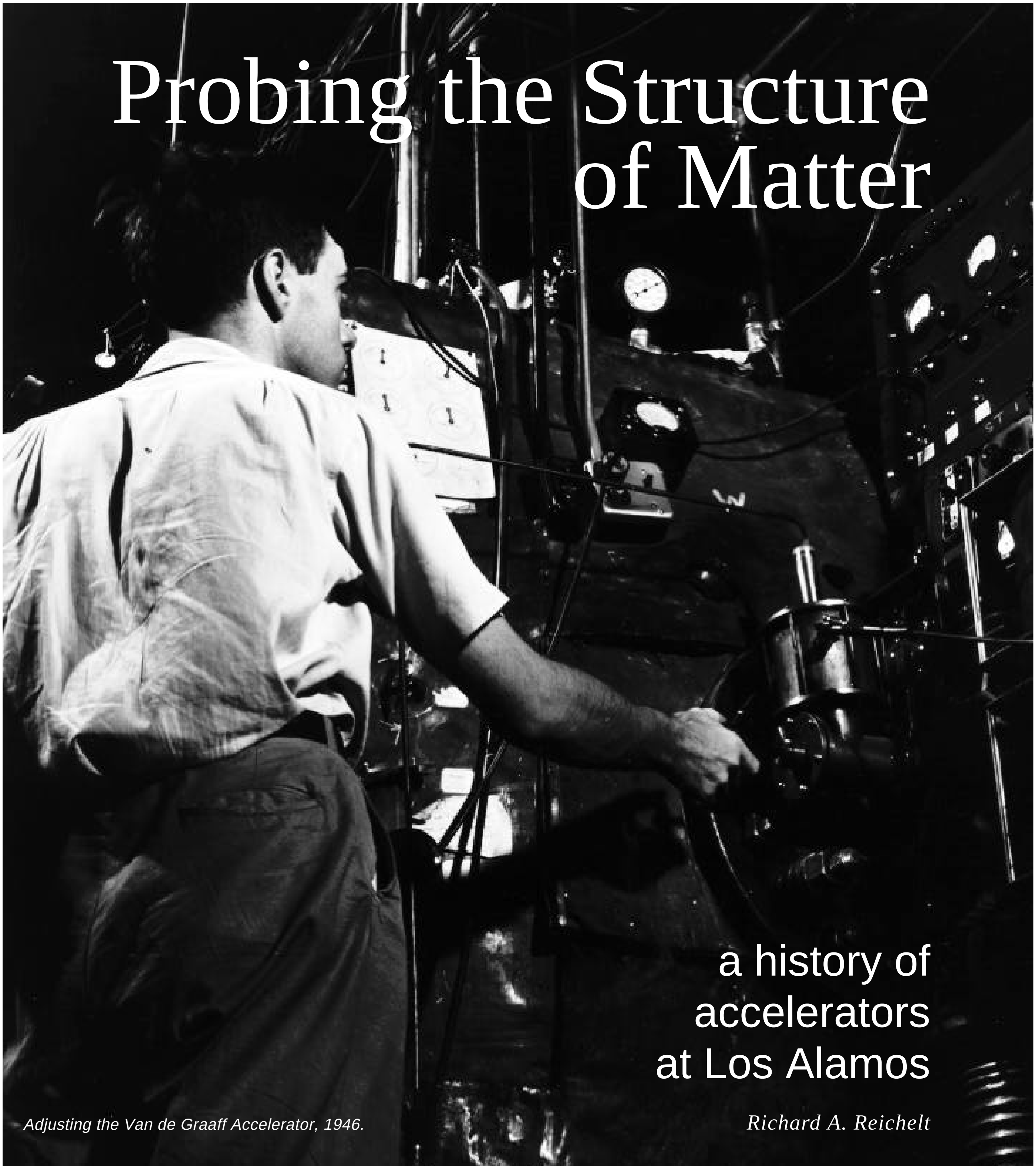


Adjusting the Van de Graaff Accelerator, 1946.

The history of Los Alamos is intimately linked to machines. Machines of all types—from reactors to computers to lasers—have been indispensable in advancing scientific knowledge at the Laboratory. Among all of those machines, accelerators occupy a special position. During World War II accelerators provided vital information to scientists designing the first nuclear weapons, and after the war some of those machines were used as tools of basic scientific research. Then, in the early 1970s, a half-mile-long accelerator called LAMPF (formally named the Clinton P. Anderson Meson Physics Facility) was completed after a decade of planning and construction. Over the years LAMPF has been the workhorse for many Laboratory programs, including programs in nuclear physics, weapons research, neutron scattering, radioisotope production, and pion cancer therapy. Accelerators for more specialized purposes have also been developed or improved by Los Alamos scientists.

The constant effort to upgrade and redesign accelerators has often led to unexpected results. New technological spin-offs, new vistas of scientific research, have opened up as one generation of machines replaced another. This photoessay briefly traces the evolution of accelerators at Los Alamos and examines their different applications. In the last section the promise of a future generation of machines is examined.

First a few words of explanation. Most accelerators work according to the same basic principle. An electric field is applied to a stream of charged particles (typically electrons or protons) and accelerates the particles to greater and greater energies. Those accelerated particles can then strike a target and interact with the target atoms. If the particles have a high enough energy, they interact with the nuclei of the atoms, often yielding "secondary" particles whose identities depend on the energy of the primary particles and on the target material. Sometimes the accelerated particles are only a means of producing the secondary particles (neutrons and pions are examples of secondary particles). Although the basic principle of particle acceleration is simple, its execution is not. Designing an accelerator requires creativity and ingenuity, and operating an accelerator can be an art in itself.

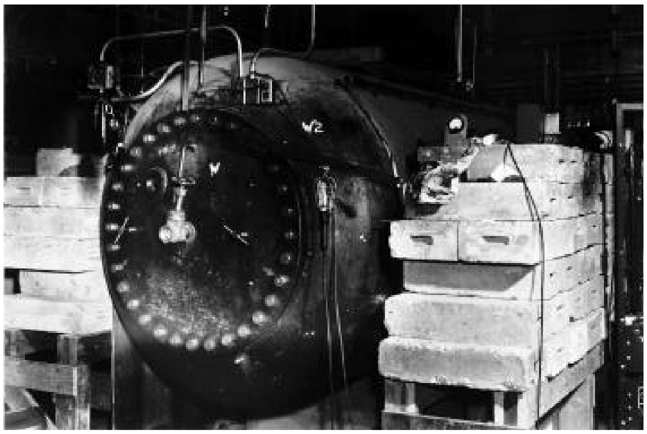
Technical Building Z. *This shack was built for the Cockcroft-Walton accelerator in 1943.*

Most modern accelerators are classified as either linear accelerators (linacs) or circular accelerators. The linac design, in which the accelerated particles move in a straight line, was first developed by Rolph Wideröe in 1928 and later refined by Luis Alvarez. The circular machine, in which the particles move in a circular path, was conceived by Ernest Lawrence in 1929. He called his invention the cyclotron.

World War II Accelerators

J. Robert Oppenheimer, director of Project Y during World War II, was responsible for bringing accelerators to Los Alamos. He believed that only by consolidating machines and scientists in one location could a nuclear bomb be speedily built. And speed was important—the Germans were thought to be well advanced in developing a nuclear bomb. Oppenheimer envisaged concentrating the work of designing and building the the first nuclear bombs in one location so that ideas and findings could easily be exchanged. Accelerators, as suppliers of nuclear data, were urgently needed to provide an experimental foundation for the work.

Thus, in the spring of 1943, four bulky machines were transported to a remote New Mexico location from



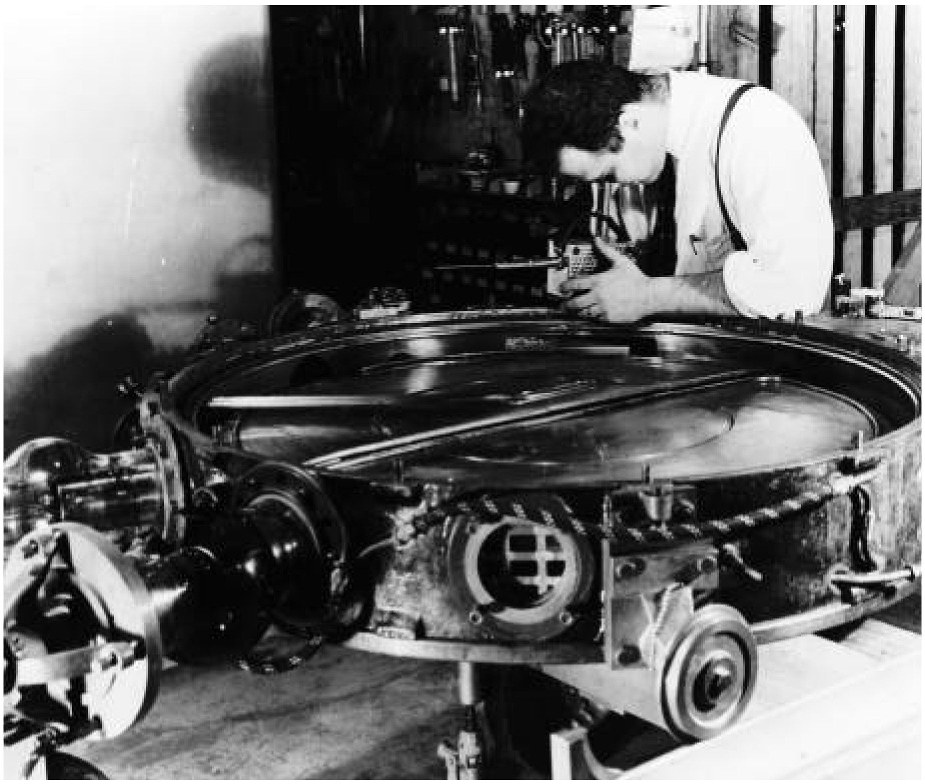
The Wisconsin Short Tank. *One of five accelerators commandeered for use at Los Alamos during World War II, the Short Tank was an improved version of a Van de Graaff accelerator and was designed mainly by Joseph McKibben at the University of Wisconsin. The lead shielding and concrete blocks surrounding the pressure vessel served as radiation protection.*

universities across the country. To throw curious observers off the track, the accelerators followed a circuitous route. They were first diverted to a medical officer in St. Louis and then shipped in boxcars to Santa Fe. Finally the accelerators were moved on flatbed trucks to Los Alamos, just as some of the world's most eminent scientists were beginning to gather there. Massive steel pressure tanks for some of the machines arrived during technical conferences in mid April.

The accelerators, it was hoped, would help scientists tackle two major challenges. The first was to determine the critical masses of the proposed nuclear fuels—plutonium (^{239}Pu) and uranium highly enriched in the isotope ^{235}U. (The critical mass is the smallest mass of nuclear fuel of a certain shape necessary to sustain a chain reaction.) Both fuels were so scarce that direct measurements of the critical mass were impossible; production techniques for the fuels were only just being developed. The second challenge was to find a way of preventing a "fizzle," or predetonation, in the plutonium bomb—a problem arising from the spontaneous fission of fuel impurities. Of the two problems predetonation was the more intractable and the source of pessimism about the feasibility of a plutonium bomb.

The accelerators made it possible for scientists to determine the critical masses for each proposed bomb design. The machines supplied neutrons for studying the neutron interactions involved in an explosive fission chain reaction. At that time neutron-induced fission—the process by which a neutron causes the nucleus of a heavy atom to split and release energy and more neutrons—had not been studied at all the relevant neutron energies. Several months earlier, in December, 1942, Enrico Fermi had induced the first fission chain reaction at the University of Chicago using a "pile" consisting of enriched uranium interleaved with graphite moderators. The moderators were designed to slow down neutrons and make the fission reaction more efficient. But fission induced by fast neutrons was expected to be less efficient than fission induced by slow neutrons. In an explosive chain reaction there could be no moderators; the neutrons would emerge from fission at high energies—between 0.1 and 3 MeV (1 MeV = 1 million electron volts)—and travel unimpeded until they collided with other heavy nuclei. How would the fast neutrons interact with heavy nuclei? What percentage of those neutrons would

The Illinois Cockcroft-Walton Accelerator. *This accelerator was used by John Manley and his group to investigate the efficacy of different metals as a "tamper"—a liner surrounding the nuclear explosive that acts as a neutron reflector and makes the explosive chain reaction more efficient. Gold, uranium, platinum, tungsten, and other metals were investigated as possible tampers.*



A Portion of the Harvard Cyclotron. *A group led by R. R. Wilson investigated nuclear reactions induced by the low-energy neutrons provided by this 42-inch cyclotron.*

cause fission? How many neutrons would be released in a fission reaction caused by a fast neutron? What percentage would be reflected back into the fissile material from a metal liner—or "tamper"—surrounding the core? As sources of neutrons with various energies, accelerators were just the tools scientists needed in order to study the nuclear reactions relevant to weapons physics.

Within a few months of their arrival, all four accelerators were producing neutrons in hastily erected wooden buildings. A Cockcroft-Walton accelerator requisitioned from the University of Illinois produced 2.5-MeV neutrons. Two Van de Graaff accelerators from the University of Wisconsin produced neutrons with energies between a few hundredths of an MeV and several MeV. And a cyclotron from Harvard University produced neutrons with even lower energies. Together the accelerators produced neutrons with energies spanning the pertinent energy spectrum.

The summer of 1944 signaled an abrupt shift in the program at Los Alamos. In mid April Emilio Segré and his band of graduate students had discovered some bad news—that ^{240}Pu (an isotopic impurity present in ^{239}Pu) had a high cross section for spontaneous fission. The original plan for initiating an explosive fission chain reaction in either a plutonium or a uranium bomb had been to use a gun mechanism to fire one subcritical chunk of nuclear fuel into another subcritical chunk. But if the fuel was plutonium, the neutrons produced by the spontaneous fission of ^{240}Pu were likely to initiate a chain reaction in the two chunks before the gun mechanism could bring them together into a supercritical mass. The result would be a fizzle. Therefore a gun-type plutonium weapon was out of the question. So in August the Laboratory threw its resources into achieving criticality in a plutonium weapon by implosion, that is, by detonation of a layer of conventional explosives surrounding a subcritical sphere of plutonium. The idea was that the inward force of the conventional explosion would compress the plutonium sphere and thereby create a supercritical mass, provided the implosion was sufficiently symmetric. The implosion option had been pursued previously—early experiments had involved detonating TNT wrapped around iron pipes—but implosive forces of the required symmetry had not been achieved.

To help in the design of an implosion weapon, a betatron—a circular electron accelerator— was procured in December, 1944. Pulses of x rays produced by the betatron were used to obtain a sequence of images of a sphere of mock fuel as it was being imploded by a particular configuration of high explosive. This diagnostic technique, along with others, helped solve the problem of uneven collapse in the implosion weapon.

On July 16, 1945, a plutonium weapon was tested near Alamogordo, New Mexico. On August 6 a uranium weapon, Little Boy, was dropped on Hiroshima, Japan, and on August 9 a plutonium weapon, Fat Man, was dropped on Nagasaki. Soon after those bombing attacks Japan surrendered unconditionally. Oppenheimer's idea of consolidating scientists and machines at Los Alamos had simultaneously unleashed a horribly destructive force and helped to bring about an end to World War II.

Postwar Developments

Norris Bradbury, who became director in October, 1945, had the job of charting the direction the Laboratory would take in the postwar decades. His primary concern was to transform an institution that had been built for a short-term purpose—designing and building nuclear bombs—into an institution with long-range purposes and goals. Should Los Alamos become a nuclear-bomb factory? Or should it cease weapons work altogether? Or should it build a foundation of basic scientific research with weapons applications? Recognizing the coming competition with the Soviet Union and wanting to avoid "technological surprise," Bradbury (along with others) decided in favor of the last option. He also believed that such a program of basic scientific research would help to retain the cadre of talented individuals whose mentors had been among the brightest scientists of the twentieth century. As part of the experimental foundation for that new program, three wartime accelerators were purchased by the government—the Short Tank, the Cockcroft-Walton, and the cyclotron. The Long Tank was returned to the University of Wisconsin.

A high-energy Van de Graaff accelerator, a vertical model designed by Joe McKibben, was built to replace the Long Tank; it provided monoenergetic neutrons with energies up to approximately 8 MeV. Those high-energy neutrons and the 14-MeV neutrons provided by the Cockcroft-Walton were used to study neutron interactions relevant to nuclear fusion. The old Harvard cyclotron was upgraded into a variable-energy cyclotron that could accelerate different kinds of charged particles. Additionally, the cyclotron group developed a special camera that recorded the angular distribution of the accelerated particles after they had been scattered by the nuclei within a particular target element. Such data provide information about the energy levels of the target nucleus. Scientists' wives, many with university degrees, were enlisted to scan the photographs, becoming a team of first-rank nuclear spectroscopists.

In August, 1949, the Soviets exploded their first nuclear bomb. President Truman subsequently announced that the United States was embarking on a program to build a variety of nuclear weapons, including a fusion, or thermonuclear, bomb. Such a bomb utilizes a fission bomb to trigger the fusion of deuterium and tritium nuclei; its explosive yield is many times higher than that of a fission bomb alone. Actually, research on a fusion weapon had been pursued at Los Alamos continuously since the war years. Those early efforts were vital to the success of tests, called the Greenhouse series, that led to the first thermonuclear reaction—the George shot—in 1951.

Diagnostic tools for weapons were also developed during the early Bradbury years. Two electron linacs were built to provide radiographs of the implosion process. That work eventually led to the construction in 1963 of PHERMEX (pulsed high-energy radiographic machine emitting x rays), a huge electron accelerator, housed in a concrete bunker, that generates x rays by accelerating an electron beam onto a tungsten target. The x-ray bursts are sent through model weapons at a remote blasting site and provide three-dimensional pictures of imploding spheres. PHERMEX was also used to study fluid dynamics and the behavior of matter under extreme, shock-driven conditions. The origins of PHERMEX were in the pioneering World War II work done with the betatron. Still in operation, PHERMEX has recently been used to study the strength of ceramic tank armor.

Ten years after the war Los Alamos was still the foremost nuclear-physics laboratory in the world. Bradbury's program of basic scientific research had fed into applied fields in many ways—nuclear spectroscopy, optical modeling, and the thermonuclear weapon. But the world was catching up, and the wartime accelerators were not state-of-the-art for studying nuclei and nuclear forces. In 1946 the first proton linac—built at the University of California by Luis Alvarez, a physicist who had been involved in the nuclear-bomb project—had became operative. A linac accelerates charged particles with a series of electrical "pushes," each of which increases the energy of the particles by an amount that is small compared to the total energy gain desired. Alvarez used radar oscillators developed during the war to produce the accelerating electric field—a radio-frequency oscillating electric field—in a single long resonant cavity. Along the length of the cavity were forty-five "drift tubes" that prevented the protons from being decelerated during the negative phase of the electric field. The Alvarez design would have tremendous implications for accelerator development at Los Alamos.

An Aerial View of LAMPF in 1983.

LAMPF

LAMPF is a half-mile-long linear accelerator built atop a narrow mesa not far from Los Alamos. In 1983 Louis Rosen, the chief architect of LAMPF, described the original motivation for building the massive accelerator as follows:

T*he most fundamental reason we advanced [for requesting funds of Congress] stemmed from a belief, still held today, that eventually this country and the entire industrialized world will be forced, whether they like it or not, to a nuclear-energy economy. … We are simply running out of conventional organic sources* *of energy. … If a nuclear-energy economy is inevitable, how can we make it as efficient and safe as possible? With advanced nuclear technology. The reason we are doing so badly now with power reactors is that we didn't start with enough technology. And because technology is the child of science, we need a strong science base. Without that base, technology cannot advance and will soon dry up. We felt that the need for science as the basis of technology was the most compelling reason for Los Alamos to engage, at a very high level, in basic nuclear science.*

Rosen first proposed the idea of building the accelerator in 1962. In a memo to J. M. B. Kellogg, then leader of the Physics Division, he sketched the scientific importance of a "meson factory"—a new, high-intensity proton accelerator that would supply an abundance of pi mesons to study nuclear interactions and the structure of nuclei. Pi mesons, or pions, are short-lived particles that can be created by firing protons accelerated to nearly the speed of light at light-element targets. Since most accelerators at that time were being designed to achieve higher energies per particle rather than higher beam intensities (or numbers of particles per unit time), Rosen thought that a meson factory could open an entirely new realm in nuclear physics.

The memo eventually reached Bradbury and began to generate enthusiasm among scientists at Los Alamos. A small group of experimental and theoretical physicists began looking at two possible accelerator designs—the cyclotron and the linac. Both designs had disadvantages and drawbacks, but the scientists eventually decided in favor of the linear accelerator. The cyclotron couldn't achieve the necessary proton energy without an unacceptable loss in beam intensity; a then unheard-of intensity of 1 milliamperes was desired.

Victory Day: June 9, 1972. *Louis Rosen and others watch control instruments as the LAMPF linac produces its first beam of 800-MeV protons.*

The accelerator was envisaged in three stages. In the first stage a Cockcroft-Walton would accelerate the protons to a low energy (0.75 MeV). In the second stage an Alvarez-type drift-tube linac would accelerate the protons further to a medium energy (100 MeV). The third and final stage would accelerate the protons to 800 MeV. But no one yet knew how to accelerate protons to energies higher than 200 MeV.

In the face of considerable skepticism from outside experts, a small team of scientists led by Darragh Nagle and Ed Knapp began the search for a suitable acceleration scheme. They investigated many different cavity designs, including pillbox structures, cloverleaf structures, and slow-wave helices. Then, in early 1965 they perfected a design, known as the side-coupled cavity, that could accelerate high-intensity beams of protons to 800 MeV.

In 1967 a working prototype, called the Electron Prototype Accelerator, demonstrated the viability of the new cavity design. The demonstration had immediate practical consequences. Several manufacturers of x-ray machines for the medical community began incorporating the side-coupled cavity design into their new models. The result was smaller, more efficient machines. Today the side-coupled cavity is recognized as having revolutionized x-ray-therapy machines and other medical linear accelerators. Incidentally, the side-coupled cavity was never patented by its inventors.

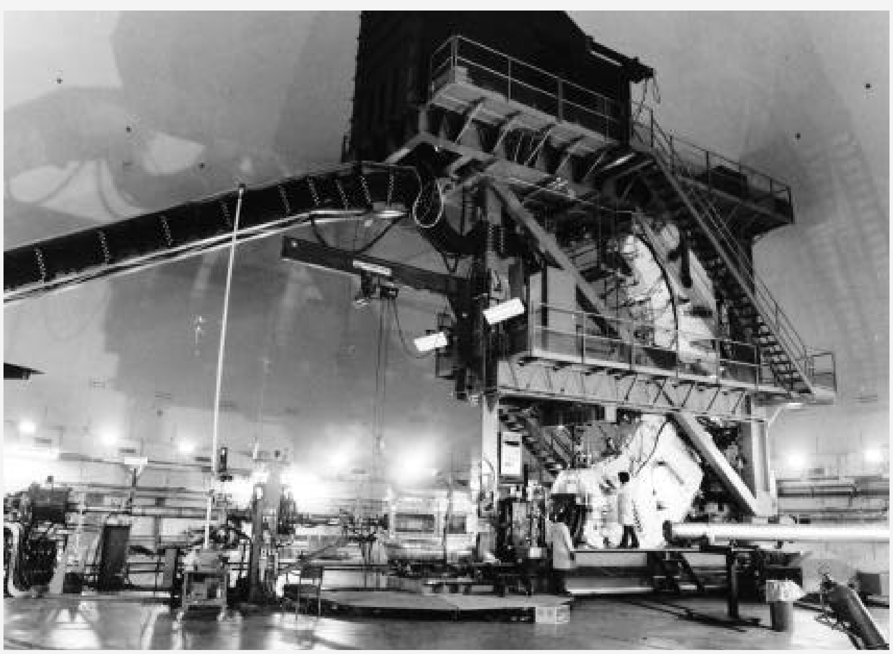
The groundbreaking ceremony for LAMPF was held on February 15, 1968. Four years later, after numerous Congressional funding battles led by Rosen, the facility was completed. LAMPF is operated as a national user facility; that is, beam time is shared among many individuals from both the United States and abroad. An international committee of experts evaluates requests for beam time and advises LAMPF's director on their scientific merit. The accelerator has spawned a remarkable number of research programs. In the area of pure science, LAMPF acts as a unique bridge between the particle-physics and nuclear-physics communities, enabling each to understand the other's methodologies and modes of thought (see "Medium-Energy Physics at LAMPF").

Medium-Energy Physics at LAMPF

Mikkel B. Johnson

The LAMPF accelerator provides primary beams of protons and negatively charged hydrogen ions as well as secondary beams of neutrons, pions, muons, and neutrinos. The uniqueness of LAMPF as an experimental facility derives from the high intensity of those beams and the consequent capability to exploit rare reactions to answer specific questions about particles and nuclei. Additionally, the high resolution of the spectrometers and other detectors available at LAMPF make precision measurements feasible. As a result, over the last twenty years LAMPF has helped to open up an entirely new field of basic research—medium-energy nuclear physics.

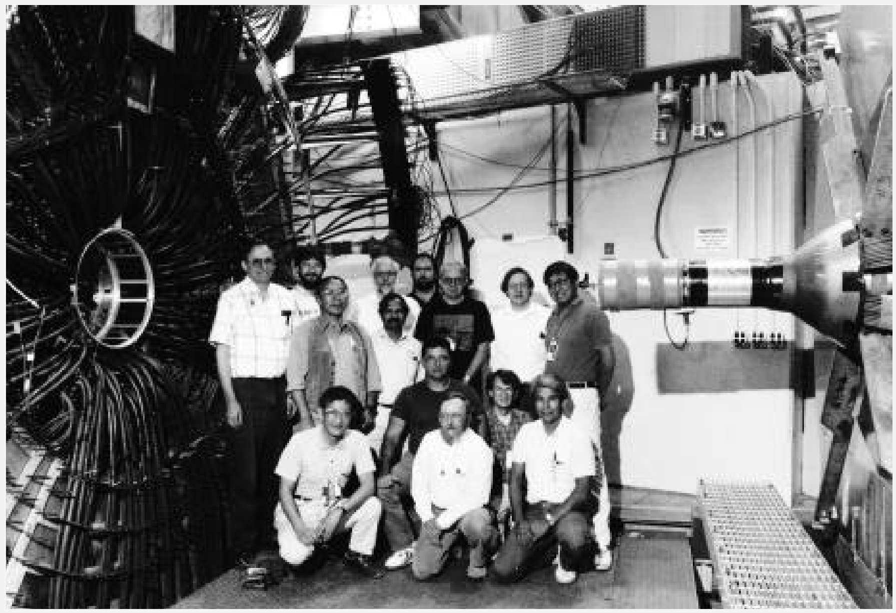
By using the tools available at LAMPF, nuclei can be explored in new ways. Experiments with muons, pions, and nucleons have quantified the size, shape, and composition of nuclear states and measured the response of nuclei to the addition of charge, energy, and momentum, as well as quanta of vibrational and rotational excitation. Some of the most interesting results have been obtained when the incoming particles cause the nuclei to respond in certain extreme ways.



The High-Resolution Proton Spectrometer at LAMPF. *This instrument, known as the HRS, is used to measure cross sections for elastic and inelastic scattering of protons from nuclei. Careful measurements with the HRS of the spin dependence of cross sections led to the widespread acceptance of relativistic descriptions of nuclear dynamics. HRS results also stimulated theoretical and further experimental investigations of how the nuclear medium affects the nucleon-nucleon interaction.*

For example, in a pion double-charge-exchange experiment, nuclei can be forced to accept two units of charge at one time. Measurements of the dependence of the scattering cross section on the final state of the nucleus have led to a strikingly detailed picture of correlations in the motion of neutrons and protons. In addition, double-charge-exchange experiments have uncovered new modes of motion of nuclei in which two patterns of vibration coexist and have also led to the discovery and study of new nuclear species. In experiments with nucleon beams, nuclei have been forced to accept a small amount of energy and at the same time a large momentum in various spin configurations hitherto incapable of being distinguished. For reasons that are not completely understood but are being actively sought, theories that work well in more normal situations have been discovered to break down under those unusual conditions. And state-of-the-art studies in atomic physics have addressed previously inaccessible regions of the spectrum with a unique technique that combines a beam of laser light and a beam of negatively charged hydrogen ions.

Additionally, various scattering experiments and measurements of the decay products of muons and pions have focused on the nature of the underlying strong, weak, and electromagnetic interactions. Precision measurements with muons have yielded new insights into quantum electrodynamics. A systematic program extending over many years has completely mapped out the character of the nucleon-nucleon interaction over the entire energy range of LAMPF and has thus provided a bank of basic data for theorists and laid the foundation for interpreting nucleon-nucleus scattering experiments. An experiment using the world's most intense source of very-low-energy neutrons has led to development of a completely new technique for detecting a signature of breakdown of a fundamental symmetry in nuclear forces. The technique, which uses properties of complex nuclei to magnify the signal for the breakdown of parity (the mirror symmetry between left and right) by a factor of about 1 million, has uncovered unexpected results and opened a rich area of exploration. Other investigations of fundamental interactions include the scattering of neutrinos from various targets. Neutrinos interact so weakly that even experiments using the high-intensity neutrino beam available at LAMPF require several years to complete. One such experiment has provided the only available measurement of electron neutrino–electron scattering. The experimental results showed that the interplay predicted by the standard model between the charged and neutral parts of the electroweak interaction was indeed a reality. Therefore, since only the neutral part of the weak force is involved in the interaction of electrons with the muon neutrino or the tau neutrino, the interaction of the electron neutrino with electrons is fundamentally different from the interaction of the other neutrinos with electrons. That difference provides a possible explanation for the observed shortfall in electron neutrinos coming from the sun. Yet other experiments at LAMPF hunt for breakdowns of the standard model. Although none has been detected, the searches at LAMPF for the decay of a muon into an electron and gamma rays, which would herald such a breakdown, have consistently led the world in sensitivity.



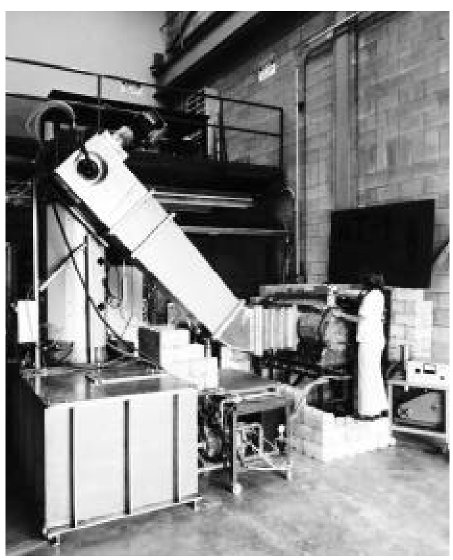
The MEGA Detector at LAMPF. *This detector will be used in a search, scheduled to begin this summer, for the decay of a muon into an electron and a gamma ray. The occurrence of that reaction would signify a breakdown of the standard model. The sensitivity of the MEGA detector to the decay is two orders of magnitude greater than that of detectors used in previous searches.*

Experiments such as those mentioned above constitute some of the highlights of the contribution of LAMPF to nuclear science. They have provided answers to many specific questions and at the same time have paved the way for a slow but very important transformation in the way nuclear physicists think about their subject. Before the era of the meson factory, nuclei could be largely understood as a collection of nucleons undergoing nonrelativistic motion and interacting through potentials. That picture is no longer adequate to describe what the medium-energy beams "see" of nuclei. To understand the new data, the catalogue of constituents of nuclei has been enlarged to encompass mesons and excited states of nucleons themselves. Additionally, the picture of the dynamics of their motion has changed. Relativity can no longer be ignored, and interactions must be described in terms of the coupling of mesons to nucleons. Even today the picture is continuing to evolve as particle and nuclear physicists realize deeper connections between their once quite distinct fields. □

Mikkel B. Johnson, a Laboratory Fellow, has pursued research in theoretical nuclear physics at the Medium Energy Physics Division since 1972.

From the beginning it was recognized that LAMPF could be a source of particles other than pions, in particular, of neutrons. Neutrons are produced at LAMPF through "spallation"—a nuclear reaction in which neutrons are knocked loose as a heavy nucleus breaks apart, or spalls, after being impacted by energetic protons. Consequently, in the early 1970s the Weapons Neutron Research Facility was built as an adjunct to LAMPF. A unique feature of the facility is a 30-meter-diameter ring of magnets called the Proton Storage Ring, a device that combines a long train of short proton pulses into a single equally short but much more intense proton pulse. Any 800-MeV proton that enters the magnetic field created by the magnets is forced to travel around and around the same circular path. Furthermore, the time required for an 800-MeV proton to travel once around the circular path is the same as the time between the short pulses that make up the long train of pulses from LAMPF. Therefore, at the instant that one proton pulse has traveled once around the circular path, a second pulse enters the magnetic field and melds with the first. Similarly, at the instant that the two melded pulses have traveled once around the circular path together, a third pulse enters the magnetic field and melds with the other two. The process is allowed to continue until all the short pulses in a pulse train have been combined into a single intense pulse. The intense pulse is then "kicked" out of the magnetic field and aimed at a tungsten target. Reactions between the protons and nuclei within the target create an intense burst of neutrons with a wide range of energies—valuable tools for studying weapons physics.

But other uses also were planned for the neutron pulses. Neutrons, unlike x rays, are scattered hardly at all by the electrons of atoms, but they are scattered by atomic nuclei. And those scatterings provide information about the structures of solid materials and of large molecules, including biological molecules, in solution. For that reason the neutron is an invaluable tool in condensed-matter physics, materials science, and biophysics. In 1986 the Department of Energy, acting in concert with various national committees, designated the WNR's neutron source as a national user facility for neutron scattering. The new facility is known informally as LANSCE and formally as the Manuel Lujan, Jr. Neutron Scattering Center. Interestingly, it is now the research at LANSCE that might be the key to LAMPF's future, as will be discussed below.



The PIGMI accelerator.

New Accelerator Technologies

Harold Agnew became Laboratory director in 1970. As a result of LAMPF's successes, Agnew decided that research on accelerator technology should receive special emphasis. A new division, called the Accelerator Technology Division, was formed in 1978. AT Division was tasked with developing new accelerator designs, and the older Medium Energy Physics Division continued operating the LAMPF accelerator, developing user programs, and pursuing nuclear- and particle-physics research.

Under the leadership of Ed Knapp, AT Division soon built prototypes of two innovative linear accelerators with medical and industrial applications. One, called PIGMI (pion generator for medical irradiations), had the potential of leading to a small accelerator—about 500 feet long—for use in cancer-treatment programs. The other was built for the Fusion Materials Irradiation Test Facility at the Hanford Site in Richland, Washington. That prototype was designed to produce neutrons with which to test different wall materials of planned fusion reactors. Both the PIGMI and FMIT accelerators employed a new acceleration device called a radio-frequency quadrupole cavity (RFQ).

The history of the RFQ is instructive because it demonstrates the way attempts to upgrade a technology can lead to new and unforeseen scientific developments. The RFQ was originally conceived by the Soviet physicists Kapchinskii and Teplyakov in 1969. It remained unknown in the West until 1977, when a Russian-educated Czech refugee named Joe Manca began working at the Laboratory. Both he and Don Swenson, who had learned about the RFQ at a Russian international conference, kept telling colleagues about the new, very efficient device for accelerating charged particles to

An RFQ Cavity. *The accelerator is shown here in front of the accelerator it may someday replace—the LAMPF Cockcroft-Walton.*

low energies. At first few people took the pair seriously, but development work at the Laboratory by Dick Stokes and others proved them to be correct. The first RFQ outside of the Soviet Union was first operated as part of the PIGMI prototype in February, 1979.

The RFQ marked an abrupt departure from previous low-energy acceleration devices. It could accelerate almost 100 percent of the beam from an ion source. And unlike the drift-tube linac, which employs a magnetic field to focus a beam, the RFQ employs rapidly alternating electrical fields to both focus and "bunch" the beam. The well-defined bunches are completely matched for follow-on acceleration devices.

Soon the RFQ played a role in a growing technological field—space weaponry. During the buildup of the Soviet arsenal in the 1970s, space weapons were contemplated as a means of non-nuclear defense. Could a beam of laser light or a beam of neutral hydrogen atoms be fired thousands of miles through space to destroy an enemy ballistic missile? The Laboratory, working on an Army project called Whitehorse, considered the possibility of neutral-particle beams as defensive weapons. Then, in the mid 1970s, using back-of-the-envelope calculations, some physicists at Los Alamos began examining the theoretical feasibility of laser-beam and neutral-particle-beam weaponry. When in 1975 John Madey and coworkers at Stanford University built a device coined the free-electron laser, its implications for non-nuclear defense were immediately recognized. Madey's device used an accelerator to create a laser beam by moving electrons past an array of magnets called a wiggler. The resulting laser beam could be tuned to any desired frequency. Interested in Madey's discovery, a small group of Los Alamos scientists designed a similar device and built a prototype of a small free-electron laser in the basement of the Laboratory's Physics Building.

In a televised speech in 1983, President Reagan called on the nation's scientific community to begin a program that would enable the U.S. to "intercept and destroy strategic ballistic missiles before they reached our own soil or that of our allies." The new program, called the Strategic Defense Initiative, was to employ two technologies that were already under development at the Laboratory: the free-electron laser and the neutral-particle beam.

At Los Alamos the first challenge in building a neutral-particle-beam weapon was to determine how launch and space environment would affect the performance of such a weapon. Consequently, on July 13, 1989, an Aries rocket with a special experimental payload called BEAR (beam experiments aboard a rocket) was launched at White Sands Missile Range. When the rocket reached its apogee, the accelerator fired a neutral-particle beam at different orientations to the earth's magnetic field. The BEAR experiment, which was a collaboration between Los Alamos scientists and industry, demonstrated that a neutral-particle beam is unaffected by the space environment and that a compact accelerator can survive launch. A key component of the payload was an RFQ.

The Ground Test Accelerator is the next step in developing neutral-particle-beam technology. In an in-

Aries Rocket at White Sands Missile Range. *This type of rocket carried into space an accelerator for producing a neutral-particle beam.*

Ground-penetrating Radar Units. *These units are effective at testing the integrity of shallowly buried fuel-storage tanks. Depth penetration is up to tens of meters in lossy soils and up to a kilometer under ice.*

dustrial partnership with Grumman Corporation, the Laboratory is building a large facility to test whether such a device can do its intended job in space. And Los Alamos and Livermore national laboratories are contributing to development of free-electron-laser weapons by providing technical expertise for the Ground-based Free-Electron Laser Project being undertaken at White Sands Missile Range.

Into the Future

Prompted by the end of the Cold War, Siegfried Hecker, director since 1986, has begun to reshape the direction of the Laboratory. Although the stewardship of nuclear weapons and other defense interests remain the highest priorities, many of the new programs are aimed at enhancing the United States's economic and industrial competitiveness. Efforts to apply accelerator technology to production of silicon chips, transmutation of nuclear waste, developing sources for neutron scattering, and cleanup of hazardous waste are being pursued. Also being investigated are advances in accelerator technology through the use of superconducting materials and microwaves.

AT Division, under Stanley Schriber, has begun a gradual shift from nuclear science toward materials science. Accelerators that were developed for SDI turn out to have many applications in materials research. For example, efforts to upgrade the present generation of free-electron lasers have great potential for processing of materials, surfaces, and chemicals. One example is silicon-chip production. The so-called Advanced Free-Electron Laser is a compact, portable free-electron laser that can be tuned to very small wavelengths—in the extreme ultraviolet—to etch silicon chips. The eventual goal of the program, led by

Rich Sheffield, is to produce a gigascale chip, one including about a billion components. A free-electron laser might be used also to liquefy methane gas at remote refineries in Alaska or Australia to enable safe transport to stateside refineries. In October, 1992, the world's first portable free-electron laser—not much larger than the bed of a pickup truck—produced its first beam at Los Alamos. Other SDI spin-offs include focusing and alignment devices for accelerators, new telescope technologies, and technologies that support the Superconducting Super Collider planned to be built near Dallas, Texas.

SDI accelerator developments have also made possible a variety of future applications that require average powers much higher than the power of LAMPF, presently the highest-power accelerator in the world. A conceptual design for the Accelerator Production of Tritium (APT) system is being developed by a team involving Los Alamos, Sandia, and Brookhaven National Laboratories and six companies. Tritium is an essential component of U.S. nuclear weapons; since it decays it must be regularly replaced. The APT system could provide a non-reactor source of tritium for the future. Related applications of high-power accelerators could include destruction of excess plutonium, nuclear-waste transmutation, and electric-power production; these applications are being evaluated by the National Academies of Science and Engineering. (See "Acceleratorbased Conversion of Surplus Plutonim.")

Other efforts by AT Division exploit new developments in materials science. One group, led by Joe DiMarco, is investigating the fabrication of accelerator cavities from niobium, a material that, when cooled to temperatures below 9 kelvins, becomes superconducting. The cost of niobium itself and of developing the fabrication technology might be offset by savings in radio-frequency-power costs. Another group, led by Bob Hoeberling, is developing a ground-penetrating radar that is capable of testing the integrity of buried gasoline and waste tanks—a potentially invaluable tool in hazardous-waste cleanup.

The trend toward materials science may also affect LAMPF. As discussed in "Neutrons in Our Future: A Proposed High-Flux Spallation Neutron Source," the Laboratory hopes to upgrade LAMPF so that it could produce more intense neutron pulses. The Laboratory's neutron scattering center would then be competitive with the most advanced neutron-scattering facilities in the world and would have significant implications for the United States's ability to develop new technologies in materials science. ■

The Clean Room at Accelerator Technology Division. *Superconducting accelerator cavities of niobium are fabricated under conditions of extreme cleanliness.*

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Accelerator Based Conversion of Surplus Plutonium

Reductions in the number of nuclear weapons in the United States and the former Soviet Union have resulted in tons of weapons-grade plutonium that need to be disposed of safely. Storage facilities are needed for the near term, but the ultimate disposition is also important. Some solutions involve converting the plutonium to a form similar to other high-level wastes destined for geologic repositories, such as spent reactor fuel and glassified wastes. Those forms would be substantially more proliferation-resistant than the present concentrated form. Even so, plutonium originating from weapons programs and the larger, growing quantities of plutonium from commercial spent fuel would continue to present a proliferation nuisance.

The Accelerator Based Conversion (ABC) technology under investigation at the Laboratory and illustrated in the figure could be used to destroy plutonium from both weapons and commercial reactors. The technology is being designed to transmute the “dominant” long-lived radioactive products generated during plutonium consumption (those that are most difficult to dispose of safely) and to generate electric power from the heat released by the various conversion processes. Initially, ABC systems could destroy the plutonium returned from the weapons program. They could also reduce the long-term toxicity of existing defense wastes destined for a geologic repository. In the longer term ABC plants could consume plutonium, other actinides, and dominant long-lived radioactive waste present in spent fuel from nuclear reactors. Accelerator-based conversion systems would transmute these long-lived radioactive materials into stable or short-lived fission products. The controlled consumption of plutonium afforded by ABC technology could thus provide an international method to reduce opportunities for proliferation.

As shown in the figure, the ABC system uses a proton beam from the accelerator to produce an intense neutron source at the target. The blanket surrounding the target contains plutonium and other actinides that are to be destroyed. The neutrons from the target are moderated, or slowed down, in the blanket, where they induce fission of the unwanted materials, which, in turn, releases more neutrons. Some of these neutrons are captured in the nuclei of long-lived fission products and thereby transmute those nuclei to short-lived or stable products. The intense flux of thermal neutrons allows the ABC system to have lower inventories of actinides and fission products for a given burn rate of those materials than other proposed systems for burning plutonium and long-lived wastes. Further advantages include smaller end-of-life inventories and potential safety enhancements. The fast burn-up of material in the ABC method requires frequent chemical processing to remove the stable and short-lived products for disposal. The unfissioned actinides, including plutonium, and dominant long-lived fission products are returned to the blanket for further exposure to the high neutron flux. The addition of accelerator-produced neutrons to the blanket not only ensures that adequate numbers of neutrons are available to transmute all of the unwanted materials but also provides for subcritical operation in the blanket and therefore prompt control of fission reactivity. This type of control may prove to be particularly advantageous in designs involving very high neutron fluxes and continuous flow of material through the blanket. The heat generated by fission in the blanket is converted to electric power. Some of this electric power can be used to run the accelerator, and the rest can be made available to the electric-power grid. □