The B-Factory and the Big Bang

Nearly 200 Livermore Laboratory specialists in accelerator technology and advanced manufacturing are helping to design and produce major components for the B-Factory at the Stanford Linear Accelerator Center, where experiments should reveal why so little antimatter is left over from the Big Bang.

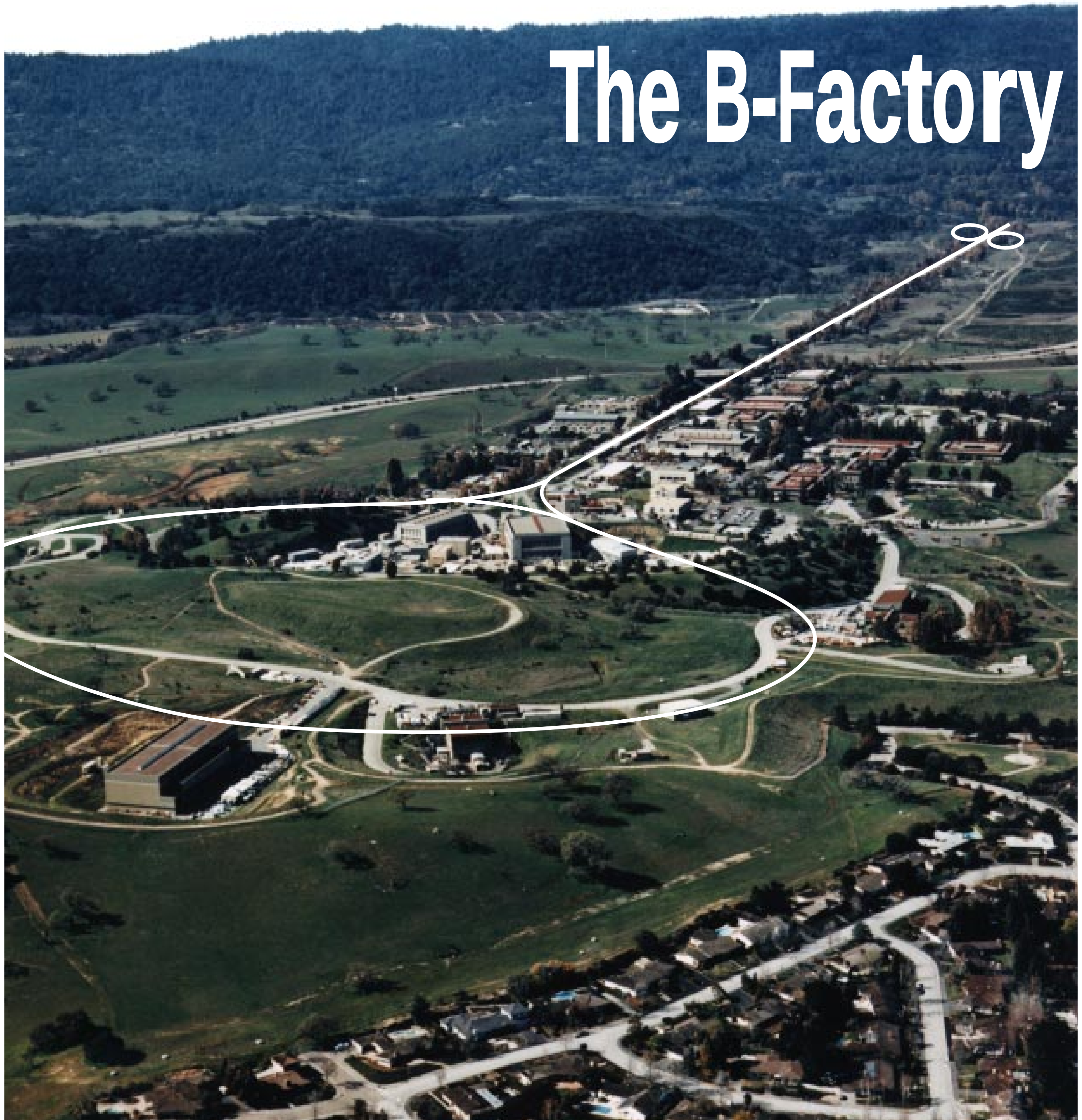

Figure 1. The B-Factory is under construction at the Stanford Linear Accelerator Center near Menlo Park, California. It consists of a portion of the existing 3.2-kilometer- (2-mile-) long linear accelerator, a new set of circular storage rings for electrons and positrons, and a large detector. (Photo courtesy of the Stanford Linear Accelerator Center.)

ONE of the great mysteries of the universe is the overwhelming preponderance of matter over antimatter. Physicists believe that a few trillionths of a second after the universe was created—the so-called Big Bang—matter and antimatter existed in equal amounts. And yet, the known universe today is overwhelmingly made of matter, the result of some process long ago that must have favored matter over antimatter (see the box on p. 12).

Physicists believe the key to unraveling this mystery—and discovering the ancient origin of matter—is to follow closely the decay of a pair of artificially produced, extremely short-lived particles of matter and antimatter, the B meson and its antiparticle. A serious investigation, however, requires a “factory” designed to produce 30 million pairs of B mesons and anti-B mesons each year. Such a facility, a virtual “time machine” back to the earliest moments of the Big Bang, is now under construction at the Stanford Linear Accelerator Center (SLAC) near Menlo Park, California (see Figure 1).

Total project cost is $300 million, including the accelerator ($177 million), the detector ($73 million), and research and development costs. The B-Factory accelerator portion is a combined effort of SLAC, Lawrence Berkeley National Laboratory, and Lawrence Livermore National Laboratory.

The B-Factory’s two underground rings, each 2,200 meters (a mile and a half) in circumference, will generate B mesons by colliding electrons and positrons (the antimatter counterpart of electrons) moving at near the speed of light. In helping to design and manufacture many of the major components and systems for the B-Factory rings and its giant, three-story-tall detector, Lawrence Livermore is strengthening its reputation as a world-class center of excellence for accelerator science and technology and high-energy physics. Nearly 200 Laboratory specialists representing a broad range of disciplines, from electroplating to particle physics, are contributing to the B-Factory effort.

The B-Factory work is only the latest chapter in a long history of Lawrence Livermore accelerator projects. Many have been built at Livermore, including the Advanced Test Accelerator, Flash X-Ray Facility, Experimental Test Accelerator, and LINAC, a 100-million-electron-volt linear accelerator. A team of Lawrence Livermore engineers and physicists contributed to designing parts

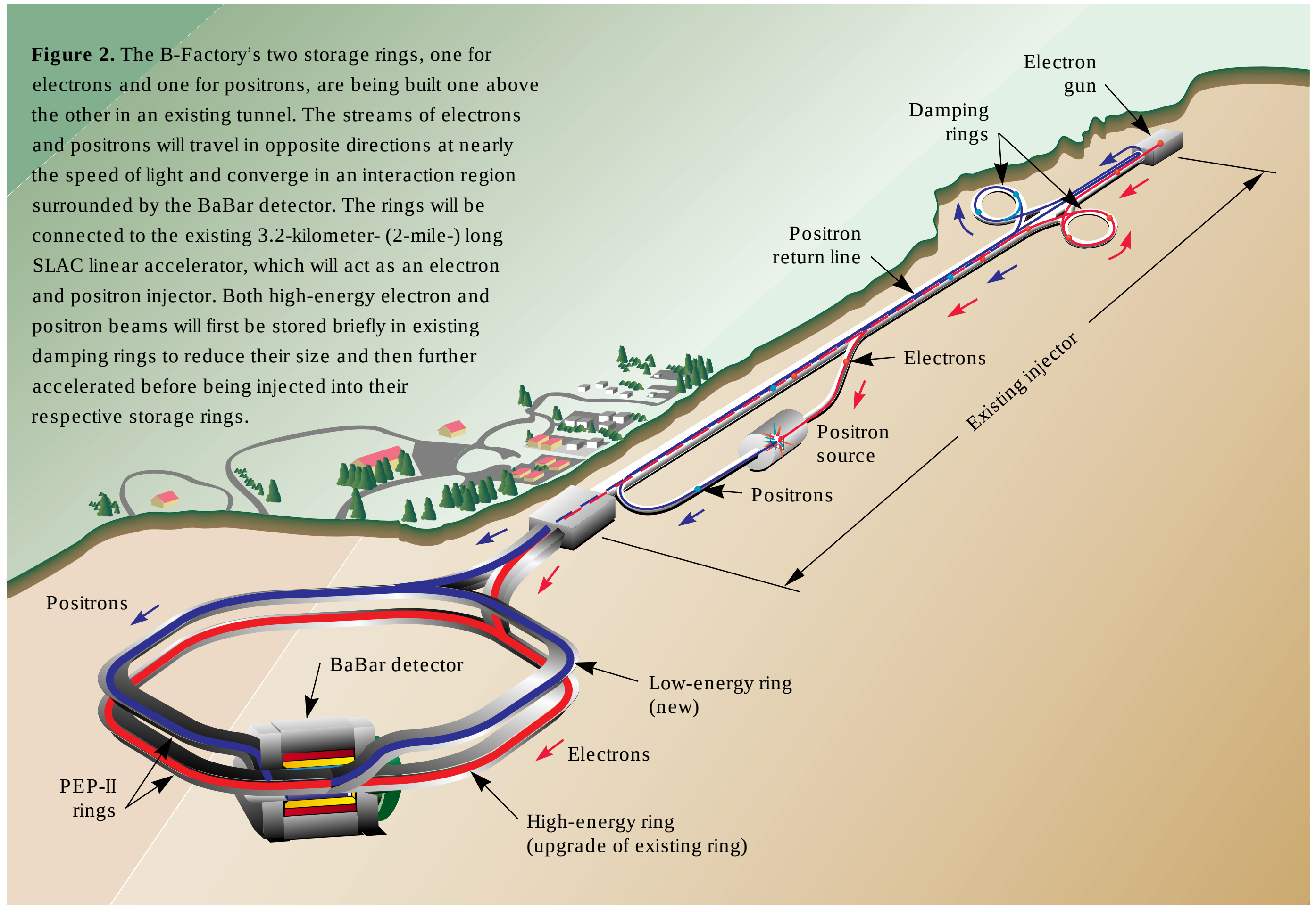

Figure 2. The B-Factory's two storage rings, one for electrons and one for positrons, are being built one above the other in an existing tunnel. The streams of electrons and positrons will travel in opposite directions at nearly the speed of light and converge in an interaction region surrounded by the BaBar detector. The rings will be connected to the existing 3.2-kilometer- (2-mile-) long SLAC linear accelerator, which will act as an electron and positron injector. Both high-energy electron and positron beams will first be stored briefly in existing damping rings to reduce their size and then further accelerated before being injected into their respective storage rings.

of the Department of Energy's Superconducting Super Collider before that enormous project was canceled. Accelerator work continues today in support of projects nationwide for the U.S. Department of Energy and overseas for Europe's nuclear research agency, CERN.

Accelerators also form a basic component of Lawrence Livermore programs. Examples include heavy-ion fusion research for inertial confinement fusion, the Center for Accelerator Mass Spectrometry for environmental research, and a host of accelerator-driven projects supporting the DOE's science-based Stockpile Stewardship and Management Program. Accelerator science is even impacting Lawrence Livermore health-care research efforts, where the Peregrine computer simulation code adapts nuclear particle transport software to optimize radiation therapy for cancer patients.

Physicist Karl van Bibber, Livermore project leader for the B-Factory, suggests two key reasons for Lawrence Livermore's important contributions to past accelerator projects and its high potential for future successes. The first is the Laboratory's longstanding experience in managing large-scale, multidisciplinary, and multilaboratory projects. The second reason is the concentration of experts in such fields as computer simulation, lasers, advanced manufacturing, precision engineering, pulsed power, and materials science, who combine to form multidisciplinary teams producing innovative accelerator component designs, engineering concepts, and manufacturing technologies.

Serving as a U.S. Flagship

Livermore accelerator expertise is most visible in its contributions to the B-Factory. Scheduled for completion in early 1999, the facility will be one of the flagships of the U.S. high-energy physics program, along with Fermi National Accelerator Laboratory's main ring injector upgrade to the Tevatron accelerator. Thousands of components, many of which will define the state of the art in accelerator technology, are being designed and built by the three partnering laboratories, which are working closely with a host of small and large U.S. contractors.

The B-Factory accelerator will consist of two storage rings built one above the other in an existing tunnel at the east end of SLAC (see Figure 2). The upper ring is for positrons; the lower for electrons (Figure 3). The rings will be connected to the existing 3.2-kilometer- (2-mile-) long SLAC linear accelerator, which will act as a particle injector. The positrons will be generated part way along the linear accelerator by crashing high-energy electrons into a cooled rotating tungsten target. Both the electrons and positrons are stored in existing damping rings, which will shrink the size of the beams, before they are reinjected and accelerated down to the storage rings. The streams of electrons and positrons travel in opposite directions at nearly the speed of light within 10-centimeter- (4-inch-) diameter metal beam pipes. Magnets guide these streams and narrow them to beams that are 1 to 2 millimeters wide. By the time the beams collide in the middle of the detector, they are flat "ribbons," about 6 micrometers high and 150 micrometers wide.

The construction project is making use of much of SLAC's existing PEP (Positron–Electron Project) facility. Work involves renovating the existing high-energy PEP storage ring for the electrons, adding a new low-energy storage ring for the positrons, and installing a huge detector called BaBar* that encompasses the central part of the interaction region where the electrons and positrons are made to collide.

A key feature of this collider is that electrons and positrons will circulate and collide with unequal (or asymmetric) energies so scientists can better study the particles generated in the collisions. The electrons will be accelerated to 9 billion electron volts and the positrons to 3.1 billion electron volts. The asymmetric energy of the colliding electrons and positrons will create B mesons and anti-B mesons with a "kick" forward, away from the collision point, making it easier for the massive detector to pinpoint the origin of the B particles' decay products.

The project is expected to generate enormous amounts of raw data each year. The data will be distributed within a collaboration that includes nearly 500 physicists representing 75 institutions in the U.S., Canada, the United Kingdom, France, Italy, Germany, Russia, China, and Taiwan. Lawrence Livermore physicists will be part of the American team analyzing the long-awaited data.

Tri-Lab Planning

Planning began in 1990 when the directors of SLAC and Lawrence Berkeley and Lawrence Livermore laboratories agreed to a coordinated research and development effort aimed at completing a conceptual design report for a B-Factory sited at SLAC. On October 4, 1993, President Clinton announced the DOE decision in favor of the SLAC–LBNL–LLNL proposal over a competing one from Cornell University.

Although SLAC is the lead laboratory, project management is drawn from the three centers. "It's hard to tell that there are three labs—it's more like one superlab," says van Bibber. The three-lab partnership is flexible, allowing it to draw upon a broad base of expertise and thereby trade or share tasks among the laboratories. Indeed, the DOE has hailed the flexibility of the project's collective management and procurement activities as a model for major science projects throughout the department.

As an example, SLAC was initially responsible for fabricating a prototype of the high-power radio-frequency

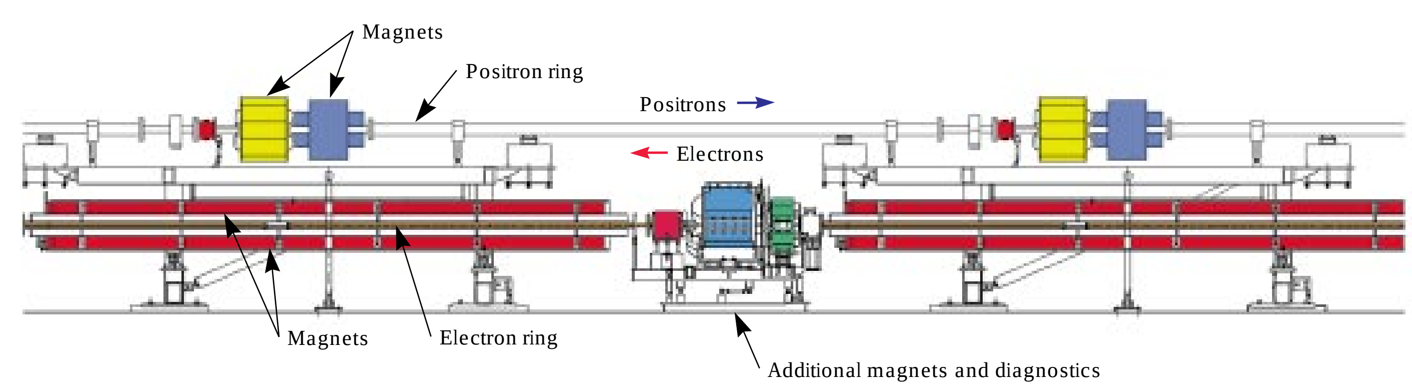

Figure 3. The B-Factory's two storage rings will be vertically stacked within the existing Positron–Electron Project (PEP) tunnel. The top ring, which is being added, is designed for positrons that will be continually guided and focused by a series of magnets. The bottom ring, designed for the more energetic electrons, requires more massive magnet systems encompassing the ring to keep the electron beams focused and on track. In the bottom center of the drawing is a complex of additional magnets and diagnostic equipment.

* The BaBar detector is named after the elephant in Jean de Brunhoff's children's stories and is a playful pun on the physics notation for B and anti-B mesons—B, $\overline{B}$—which is pronounced "B, B bar."

cavities, which will be attached in groups of two or four to 1-megawatt microwave generators to maintain the B-Factory's electron and positron beams at their proper energy levels in the high- and low-energy rings (see Figure 4). Asked to lend a hand, Lawrence Livermore assembled a multidisciplinary team, led by Manufacturing and Materials Engineering Division specialists in numerically controlled milling, precision machining, electron-beam welding, and electrodeposition. After helping with the prototype, Livermore was given responsibility to build the first 8 cavities and then all 26.

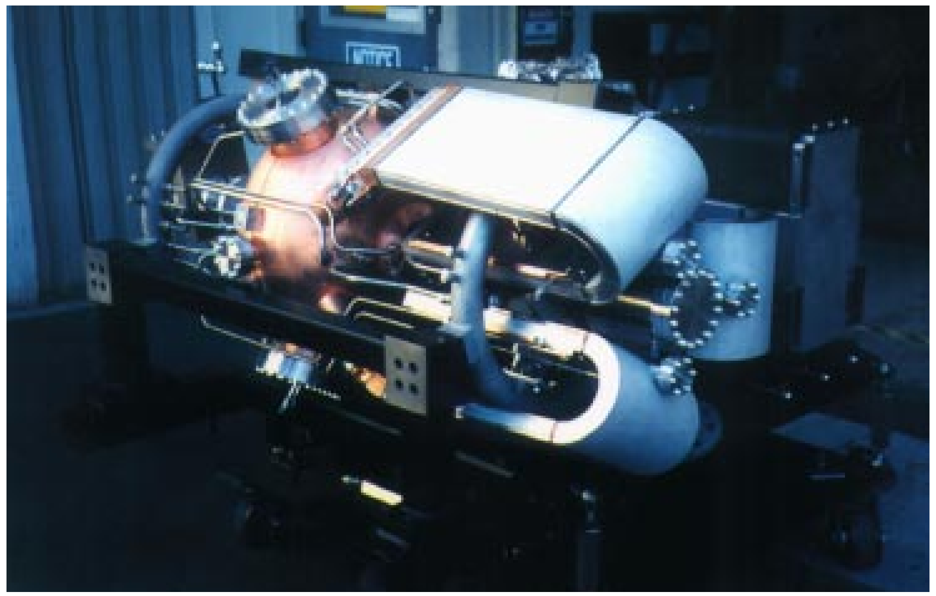

Figure 4. Twenty-six high-power radio-frequency cavities in groups of two and four will be attached to 1-megawatt microwave generators to maintain the electron and positron beams at their proper energy levels in the high- and low-energy rings. One of the spherical cavities, machined at Livermore, is shown here at the Stanford Linear Accelerator Center, where it has been attached to a host of other parts.

Livermore's Contributions

The cavities, which have an interior diameter of 50 centimeters (20 inches), were designed as the most powerful of their kind ever built. They posed exceptionally challenging manufacturing problems for Livermore engineers and technicians. For example, because the cavity wall must dissipate over 100,000 watts of microwave power, an innovative manufacturing process was developed to embed water channels in the cavity's outer surface to remove heat. First, the cavities' bowl shapes are pressed out of copper plate and then welded together using an electron beam. The channels are cut into the outside of the cavities, filled with wax, and plated with copper. The wax is melted and removed and the cavities precisely fitted with ports and flanges. (See Figure 5 for a summary of the cavity manufacturing process.)

Most of the machining is contracted to U.S. industry, with some extremely specialized fabrication and assembly activities centered at Lawrence Livermore. For example, the Laboratory's plating shop is one of the few places in the world capable of precisely electrodepositing a 1-centimeter (three-eighths-inch) layer of oxygen-free copper on the 200-kilogram (450-pound) cavities, a process that takes four weeks to complete (see May 1996 *S&TR*, pp. 28–30). All told, each cavity requires 50 different manufacturing steps and some 1,700 worker-hours to manufacture.

"Rarely in the history of the Laboratory have we faced so complex a manufacturing task as the cavities," notes Jeff Williams, head of Manufacturing and Materials Engineering Division. Williams says the task is made particularly challenging by the number of units (most of the time, the division makes one-of-a-kind items), the number of steps involved, and the number of different shops within the division that have gotten involved.

Given the original presumption that the cavities would be sole-sourced to a foreign vendor, American industry has greatly benefited from the relationship, both in new sales and new skills. "The Laboratory is acting as a master contractor. We're very proud that we're able to keep all of the work in the U.S.," says physicist Marshall Mugge, deputy project leader of the Laboratory's B-Factory activities.

Livermore experts are also cleaning nearly a kilometer of 2.4-meter- (8-foot-) long straight sections of beam pipes through a process called glow-discharge cleaning that rids the metal of residual carbon and contaminants. The process, conducted in Livermore clean rooms, is essential because an electron beam tends to attract dust particles left in the pipes much as static electricity does (see Figure 6). "Having extremely clean pipes will help ensure that the accelerator starts out with a very good vacuum," says Mugge.

Another Livermore responsibility is a critical 5-meter- (16.4-foot-) long device called the distributed ion pump. The pump will be installed within each of the 192 dipole magnets around the high-energy ring. As the particle beams circle around, they will generate a huge amount of x-ray energy, which will heat the metal pipes. The pipes in turn will discharge hot gases, which must be immediately removed to maintain the high vacuum conditions of 10^{-9} torr, or one-trillionth the atmospheric pressure of Earth at sea level.

Electrons streaming off the distributed ion pump will ionize the discharged gas, which will become quickly trapped inside the pump's cathode. Without such an effective pump, the beam would quickly attenuate by colliding with the contaminating gases. Because of the importance of

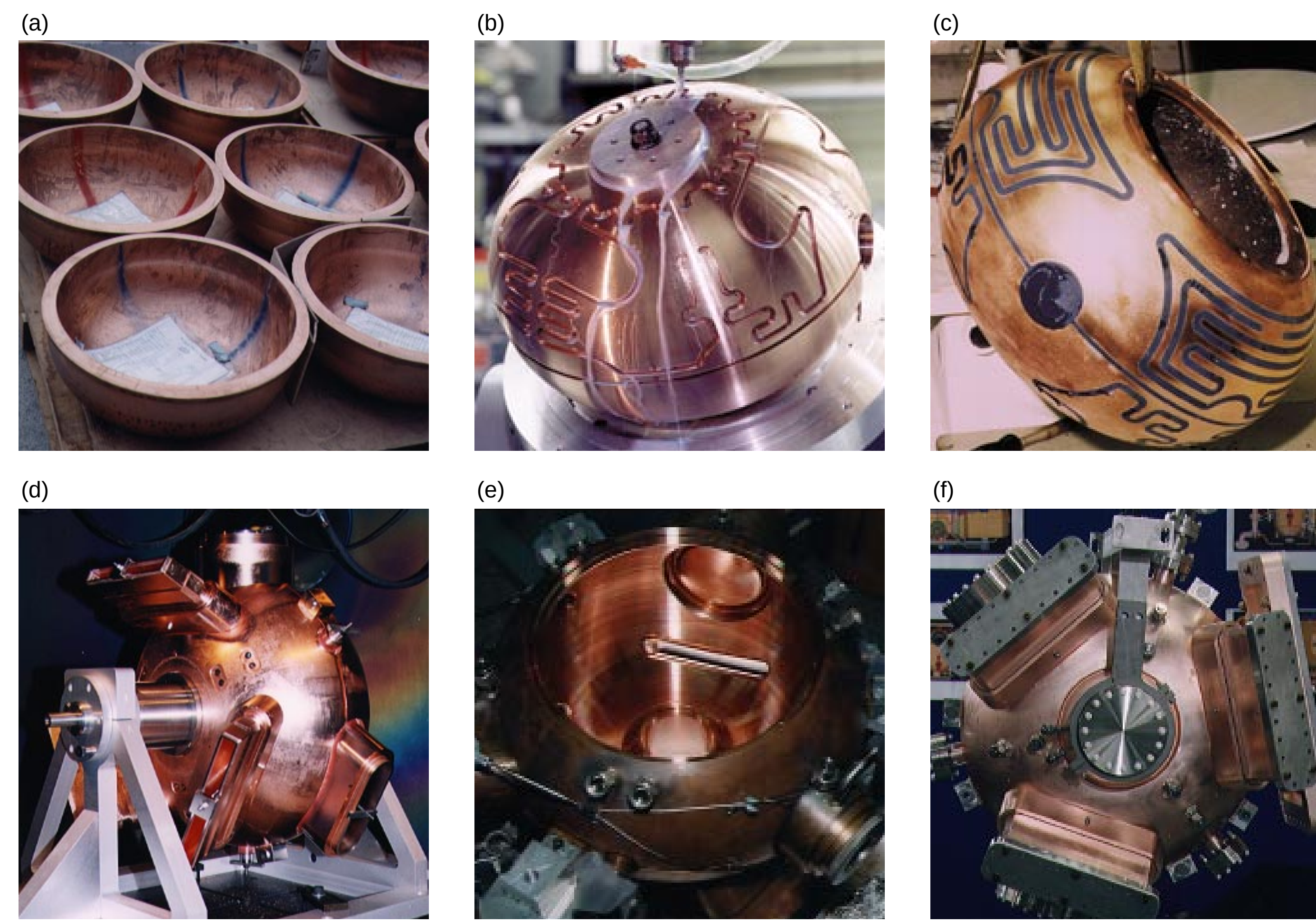

Figure 5. Six of the many steps in the radio-frequency cavity manufacturing process. (a) The radio-frequency cavities are formed from 2.54-centimeter- (1-Inch-) thick copper plates. (b) The machined bowls are electron-beam welded to form a cavity; then water channels are cut into the outer contour. (c) Wax is placed into the water channels before the cavity is plated with ultrapure copper approximately 1 centimeter (three-eighths inch) thick. (d) Several ports are attached to each cavity by electron-beam welding. (e) The cavity's surface is finished using a Livermore diamond-turning machine. (f) The final product is cleaned for ultrahigh-vacuum use and made ready for shipment to the Stanford Linear Accelerator Center for integration with other components.

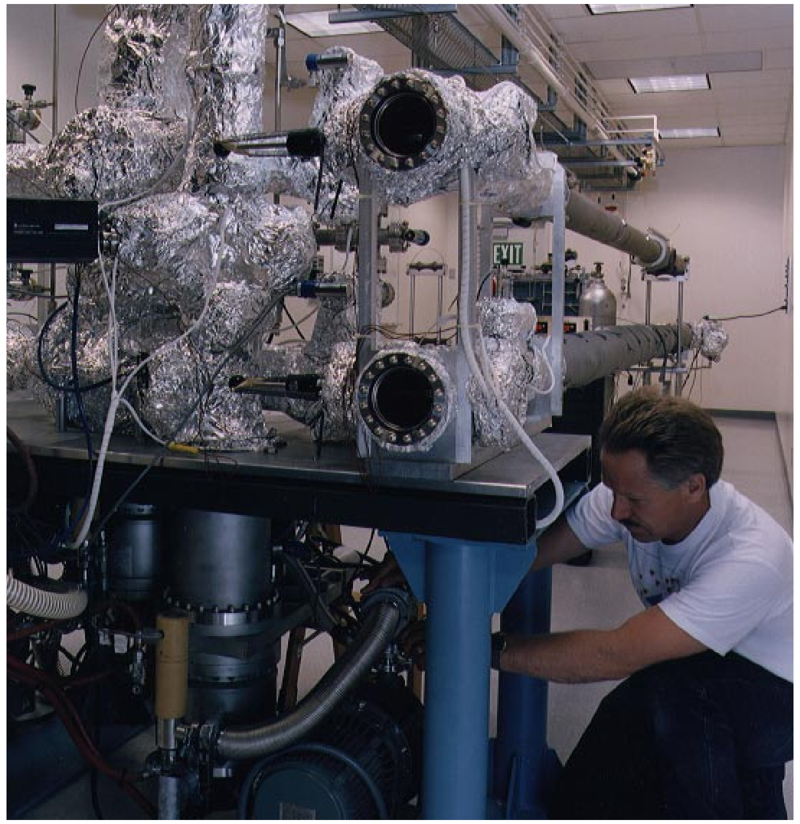

Figure 6. Livermore engineers clean nearly a kilometer of 2.4-meter-(8-foot-) long straight sections of beam pipes through a process called glow-discharge cleaning that rids the metal of residual carbon and contaminants. Here, Fred Holdener works with a vacuum pump prior to cleaning operations.

maintaining a very high vacuum, successfully demonstrating the distributed ion pump was an important factor in showing that SLAC's B-Factory design was workable.

The pump is one of several key designs produced by the 60 engineers, designers, and technicians comprising Livermore's Accelerator Technologies Engineering Group, a part of the Mechanical Engineering Department's Applied Research Engineering Division. For supervisor Lou Bertolini, the group's success is due in part to working closely with physicists in the Physics and Space Technology Directorate. Another contributing factor is the broad range of group members' backgrounds that encourages taking innovative approaches to accelerator component design.

Where Beams Collide

Among LLNL's other major responsibilities is designing and building the vacuum system and several critical diagnostic systems for the interaction region, a football-field-long assembly of magnets that guide and focus the opposing beams into the center of the giant BaBar detector (see Figure 7), where the collision occurs. Here, stability and alignment of the beam are crucial to the success of the project. For example, vacuum pressures must be extremely low—10^{-10} torr.

Without such extreme vacuum conditions, the beams would lose energy by colliding with residual air molecules. The vacuum is also necessary to reduce "noise" in the detector from interactions with gas molecules that would be confused with the large number of particles produced by B-particle decay.

"There are a tremendous number of components that have to come together at the same time in the interaction region. It's like assembling a one-of-a-kind exotic automobile," says Robert Yamamoto, deputy division leader of Applied Research Engineering Division and the coordinator for LLNL engineering work for the B-Factory.

The design of detector subsystems within BaBar has required close working relationships with research groups and manufacturers in Italy, Britain, China, and Russia. For example, the cesium iodide calorimeter, co-designed by Livermore physicists and engineers, is made of 6,000 cesium iodide crystals being manufactured in China and Russia. The 30-centimeter-(12-inch-) long crystals will measure various products from B-particle decay.

Another subsystem, the instrumented flux return (IFR), is a joint project of researchers at Livermore and in Italy. The IFR consists of a large number of specialized detectors called resistive plate chambers (RPCs). These chambers allow measurements of charged muons that traverse the outermost iron plates forming the magnetic field flux return for the BaBar detector. They also allow

the detection of certain decay products that can be used to enhance the data sample from the detector. Livermore physicists have built a special receiving and assembly area at SLAC and are now beginning to receive the first RPCs from Italian manufacturers for testing and commissioning.

Lawrence Livermore computational physicists are simulating events in the interaction region that are telling the international B-Factory research community how the detectors will track the tens of thousands of daily collisions between electrons and positrons. Livermore physicist Craig Wuest notes that the simulations are becoming increasingly realistic as detector designs are finalized and the systems manufactured and installed.

Beyond the B-Factory

The Laboratory's Accelerator Technologies Engineering Group is no stranger to large-scale accelerator projects, having done important work for the past several years for both U.S. and European experiments. Today, besides its B-Factory contributions, the group is designing and fabricating the magnet system for the Photon–Electron New Heavy Ion Experiment (PHENIX) led by Brookhaven National Laboratory. The 3,500-ton magnet system measures 10 meters high, 10 meters across, and 20 meters long (30 by 30 by 60 feet). The group is also coordinating production by Russian mills of the massive amounts of iron needed for the project. The goal of PHENIX is to look for evidence of a primordial state of matter that last existed a few microseconds after the Big Bang.

The LLNL team is likewise supporting the Main Injector Neutrino Oscillation Search (MINOS), an experiment led by Fermi National Accelerator Laboratory that will search for muon neutrinos oscillating into electron neutrinos or tau neutrinos. Livermore activities focus on engineering several components, including a detector composed of 600 octagonal plates of 8-meter-(25-foot-) tall steel. Livermore physicists are also leading the research and development of resistive-plate-chamber technology for the 32,000 square meters (8 acres) of active detectors that will be interleaved with the steel.

Enhancing Reputations

Van Bibber says Livermore's extensive B-Factory work, combined with support for other projects worldwide, augurs well for major Livermore participation in future accelerator projects. He also notes that many capabilities that are being brought to bear on the technical challenges of the B-Factory are supporting Lawrence Livermore's diverse efforts for the DOE Stockpile Stewardship Program.

"Our people have their feet in physics research as well as other applications," says van Bibber. "The solution we come up with for a B-Factory problem may also be used to solve new problems in defense sciences and vice versa."

For example, DOE's Accelerated Strategic Computing Initiative, which is being developed primarily for the

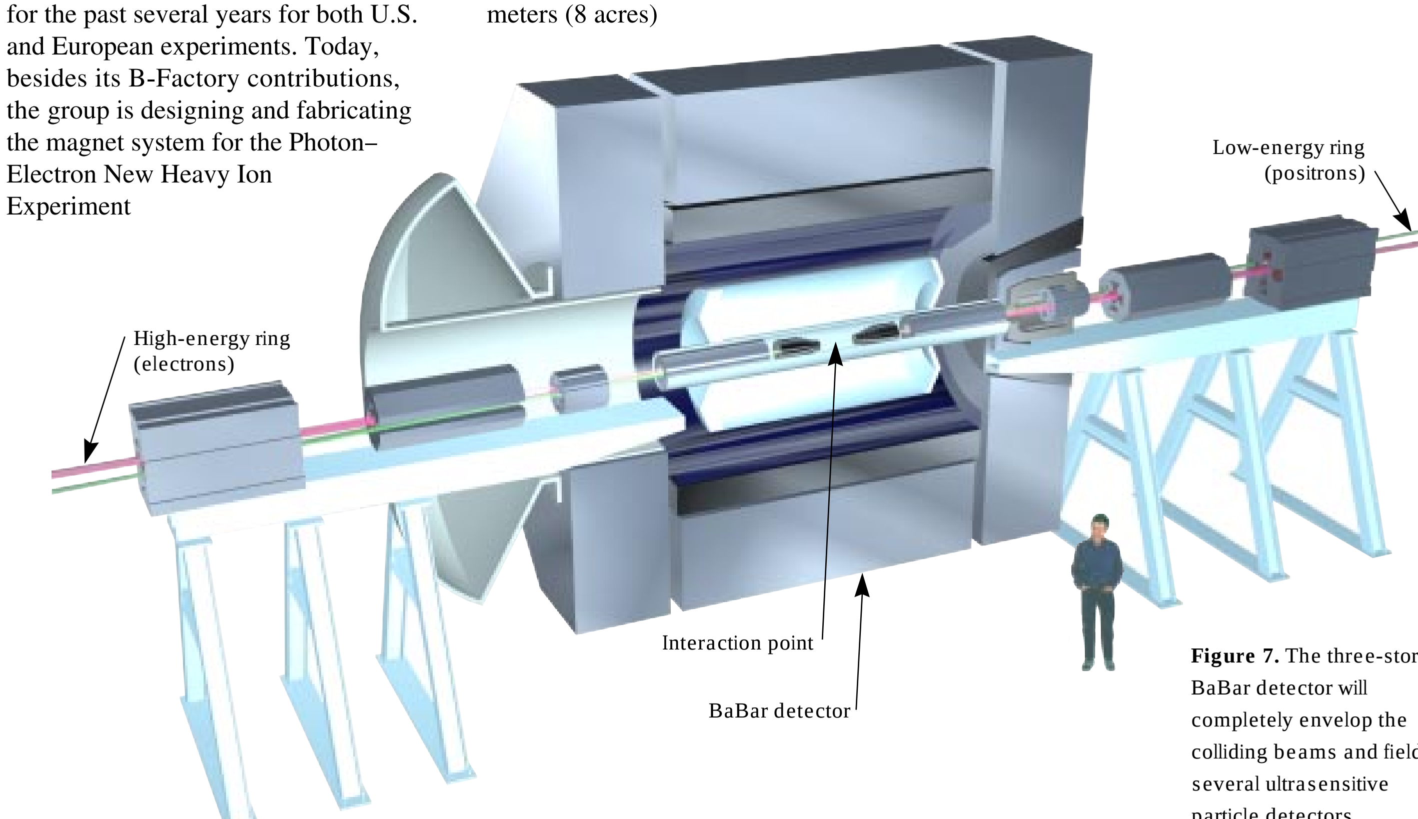

Figure 7. The three-story BaBar detector will completely envelop the colliding beams and field several ultrasensitive particle detectors.

Stockpile Stewardship Program, has direct applications to computer modeling of high-energy particle interactions. The Laboratory is also building upon its successful design of the B-Factory's distributed ion pump to design and develop the vacuum system for the Accelerator Production of Tritium facility planned at DOE's Savannah River operations. Livermore is collaborating with Los Alamos and Brookhaven on this option for cost-effectively producing tritium for the nation's nuclear stockpile.

Together with colleagues from Los Alamos, Livermore experts are also designing a new kind of camera that will use high-energy protons to penetrate thick, imploding objects and thereby reveal much more internal detail than do conventional flash x-ray machines. The proton radiography concept is under study for the DOE's Advanced Hydrotest Facility.

A Bright Future for the NLC

Laboratory physicists estimate that between now and 2010, the total budget for large accelerators in the world will total about $10 billion. The biggest American project on the drawing board is called the Next Linear Collider (NLC). The NLC is proposed as a 30-kilometer- (18.6-mile-) long facility to collide electrons and positrons at energies up to a trillion electron volts. Designed to probe more deeply the fundamental nature of the universe, the NLC requires a large luminosity necessitating that the beam width be no more than 40 atomic diameters to achieve the required data rate.

SLAC, Lawrence Berkeley, and Lawrence Livermore have signed a memorandum of understanding to collaborate on research and development for the NLC, which is expected to be built on or near an existing national laboratory by the consortium. The key to making the NLC a reality, van Bibber emphasizes, is attacking the cost of the project with advanced manufacturing methods. For example, the NLC will require the fast, cheap, and precise manufacture of 20 kilometers (12.4 miles) of linear accelerator structures. These structures will sustain the high-power microwaves on which the electrons and positrons "surf," gaining energy on their way to collision at the interaction region. The structures will be built up of two million diamond-point-machined copper cells, diffusion bonded together. Lawrence Livermore's expertise in advanced manufacturing technologies is expected to play a pivotal role in reducing costs by factors of 2 to 6 over present estimates.

While preliminary design work for the NLC is under way, a team of Livermore physicists is working to establish a center of excellence in accelerator science and technology at the 100-million-electron-volt linear accelerator (LINAC) at Livermore. The goal is to establish accelerators as a cornerstone Lawrence Livermore program by having a centralized facility for research in advanced accelerator concepts that will draw key technologies from several Laboratory directorates and programs.

An avenue of research at the LINAC that has extraordinary potential takes advantage of recent Livermore advances in high power laser technology (see the November 1995 *S&TR*, pp. 34–36, and the December 1996 *S&TR*, pp. 4–11, for descriptions of LLNL's new terawatt and petawatt lasers). Physicists plan to use a 100-terawatt (100-trillion-watt) laser built by the Laboratory's Laser Programs to explore novel acceleration methods. The results could revolutionize the design—and capability—of particle accelerators. An accelerator using laser power could in principle reduce the size of the linear accelerator at SLAC to that of a large office.

Van Bibber says that one of the primary goals of a vigorous Lawrence Livermore accelerator R&D effort is developing compact accelerators for defense, industry, and advanced research applications. Examples include developing portable accelerators to probe the interior of a small boat or truck and "interrogate" its cargo for nuclear materials or to detect land mines still buried in battle areas of Europe and Asia. Future compact electron accelerators could also make femtosecond (quadrillionth-of-a-second) x rays broadly accessible to scientists for biological or materials research.

It seems fitting that advanced accelerator technology is becoming a major focus for the Laboratory in the future. After all, it was E. O. Lawrence, Lawrence Livermore's founder, who was awarded the Nobel Prize in Physics more than 50 years ago for his pioneering work in accelerators.

—Arnie Heller

Key Words: accelerators, Accelerated Strategic Computing Initiative (ASCI), Accelerator Production of Tritium (APT), Advanced Hydrotest Facility (AHF), B-Factory, B meson, BaBar detector, Big Bang, Center for Accelerator Mass Spectrometry (CAMS), charge parity violation, LINAC, Main Injector Neutrino Oscillation Search (MINOS), Next Linear Collider (NLC), Photon–Electron New Heavy Ion Experiment (PHENIX), Stanford Linear Accelerator Center (SLAC), Stockpile Stewardship and Management Program, 100-terawatt laser.

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The Curious Case of the B Meson

Physicists believe a key to the matter–antimatter disparity in the universe lies in understanding an effect called charge parity violation. First observed in the 1960s, charge parity violation refers to the apparently small differences in the way that certain short-lived particles and their antiparticles decay. Many scientists, starting with the renowned Russian physicist Andrei Sakharov, have suggested that charge parity violation is the reason why the universe seems to be composed almost exclusively of matter. Or, as Stanford Linear Accelerator Center Director Burton Richter puts it, "Charge parity violation is why we're here."

Physicists think that the best way to understand the phenomenon is by studying the decay patterns of the rare B meson, a type of unstable but electrically neutral particle, and its antiparticle, the anti-B meson. The B meson consists of "anti-b" quark and a "d" quark (quarks are the fundamental building blocks of matter), while the anti-B meson consists of a "b" quark and an "anti-d" quark.

To measure the decay patterns of these extremely short-lived (1.5 trillionths of a second or 10^{-12} second) particles, investigators need a machine to produce a myriad of B mesons and anti B mesons. "B-Factories" at the Stanford Linear Accelerator Center and in Japan, both currently under construction, will provide literally millions of particles to study. In effect, says Livermore physicist Marshall Mugge, "The B-Factory will allow us to go back in time to reproduce the early conditions of the Big Bang."

At both factories, the B mesons and anti-B mesons will be created by colliding beams of electrons and positrons circling at different energies. Most of the electrons and positrons will miss each another. However, a few collisions will result in B meson–anti-B meson pairs. Because the electrons and positrons are circling at different energies, the B and anti-B mesons will be created with a push away from the point at which the two beams collide, clearly separating their decay vertices—up to a millimeter apart—and therefore making them easier to resolve.

The particle pairs will follow one of several different pathways as they decay into a host of subatomic particles like muons, leptons, neutrinos, and quarks. About one in every 1,000 pairs is expected to follow a unique pathway that results in a very special combination of particles that will signal to physicists a possible violation of charge parity. That is, these special pairs will decay to certain sets of particles at different rates.

Physicists will determine the rates of decay by measuring how far the particles have traveled from the interaction point. By knowing how fast the particles are traveling, scientists can determine the time that they existed before they decayed. The distances are exceedingly small—about a few hundred micrometers (less than one-thirty-second of an inch) in space. Subtle variations in the distribution of the distance traveled between the pairs will be evidence for charge parity violation.

Livermore physicist and B-Factory leader Karl van Bibber says that by the end of the first six months, there should be some "very interesting data" for 75 to 80 institutions worldwide to analyze. The data should enable scientists to better understand why the universe appears to contain essentially no antimatter. In so doing, they will be able to paint a much more complete and accurate picture of the fundamental nature of matter and energy.

About the Scientists

MARSHALL MUGGE (left) joined the Laboratory as a physicist in 1985. He served as Assistant Division Leader in the Physics and Space Technology Directorate from 1990 to 1993. From 1977 to 1985, he was a physicist at Fermi National Accelerator Laboratory. He received his B.S. in physics and mathematics from Iowa State University and his Ph.D. in high-energy physics from the University of Colorado. He is currently deputy project leader of the Laboratory's B-Factory activities.

ROBERT YAMAMOTO is deputy division leader of the Applied Research Engineering Division of Lawrence Livermore's Engineering Directorate. He earned a B.S. in mechanical engineering from the University of California, Berkeley, and an M.B.A. from Golden Gate University in San Francisco. Yamamoto coordinates the Laboratory's engineering work for the B-Factory project.

KARL VAN BIBBER is a graduate of the Massachusetts Institute of Technology, with a B.S. in physics and mathematics and a Ph.D. in physics. He joined the Laboratory in 1985 as a senior physicist. Since July 1991, he has been group leader for High-Energy Physics and Accelerator Technology in the Physics and Space Technology Directorate. He is currently the project leader for Livermore's work on the B-Factory at the Stanford Linear Accelerator Center.