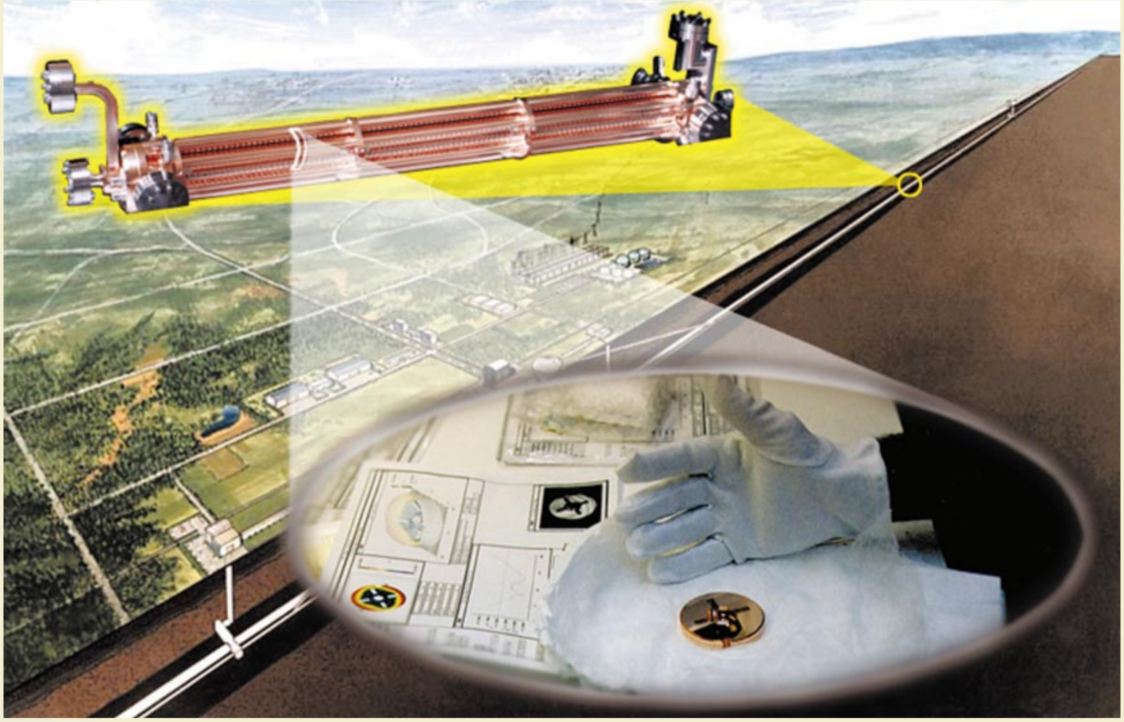
The Next Accelerator for Revolutionizing Physics

The Next Linear Collider—Getting More Bang for the Buck in Particle Physics.

HIGH-energy physics has always been a frontier discipline in science, driving technological innovation and pushing the limits of what we know about the disparate but interconnected worlds of cosmology and elementary particles.

That being the case, the proposed Next Linear Collider (NLC) could be considered the high-tech equivalent of a frontier outpost—at the edge of a new world. The NLC is being developed by a collaboration of four Department of Energy national laboratories—Stanford Linear Accelerator Center (SLAC), Lawrence Livermore and Lawrence Berkeley national laboratories, and Fermi National Accelerator Laboratory (FNAL or Fermilab). It will accelerate fundamental particles, the building blocks of our universe, to energies in the teraelectronvolt (TeV) range—that's a trillion (10^{12}) electronvolts. Physicists believe that the NLC, and other extreme high-energy particle accelerators like it, will lead the way in answering some of the most fundamental questions of science: How do particles acquire mass? What is the structure of space–time? What constitutes the dark matter of the universe?



Conceptual drawing of the Next Linear Collider, housed in a tunnel approximately 30 kilometers long inside which are two opposing linear accelerators (linacs). Within each linac, the electrons (or positrons) are accelerated within thousands of copper accelerator structures, each made up of more than 200 precision-machined copper cells (see inset). Precision machining and alignment of the cells is crucial to keep the beam bunches sharp, small, and straight.

Karl van Bibber, who leads the Lawrence Livermore effort for the NLC collaboration, notes that each decade in the 20th century has had major discoveries in high-energy physics, while continually pushing the definition of “high energy” to ever-higher values. Physicists are almost certain that truly revolutionary discoveries will be made within the next 10 years.

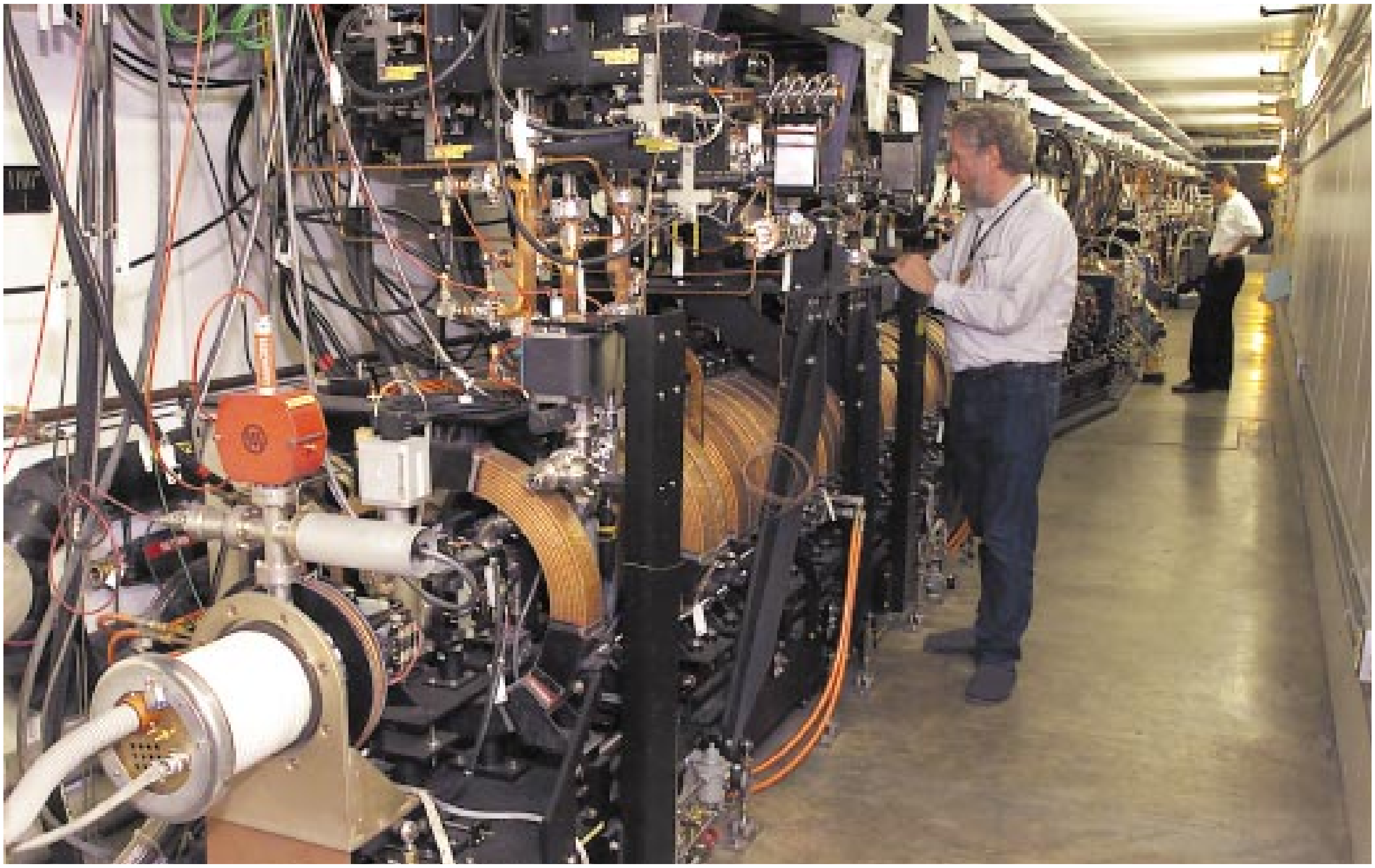
In the landscape of high-energy physics, three regions of intense activity center around major facilities: the European Laboratory for Particle Physics (commonly known by the acronym CERN from its former name) in Geneva, the Japanese High Energy Accelerator Research Organization (KEK) in Tsukuba, and Fermilab and SLAC in the U.S. Fermilab’s 2-TeV Tevatron is now the highest energy machine in the world, but CERN’s Large Hadron Collider will operate at 14 TeV once it is completed in 2005. Both of these machines are proton colliders and may well make the next discoveries in high-energy physics.

Van Bibber explains the proton collider process: “Colliding beams of protons is like smashing together two beanbags. You’re looking for the rare events where two beans inside them will undergo a hard, pointlike collision.” Because protons are made up of many quarks and gluons, new heavy particles will be created only if a single quark or gluon might collide with its counterpart in the other proton. Thus, only a small fraction of the protons’ total energy goes into creating new heavy particles. The other constituents merely create a mess of background particles of no interest.

“Studying proton collisions is a high-background and low-statistics business,” notes Van Bibber. “An electron–positron collision, in comparison, is often much more fruitful. Both the electron and the positron are pointlike fundamental objects, so when they collide, the total energy of both goes into creating new particles.” As an example of the difference, a proton collider at CERN discovered the intermediate vector boson particles—the W^+, W^-, and Z^0—which are responsible for the weak interactions, including radioactive decay. After five years or so of operation, the total number of Z^0 events created was about 100. CERN’s Large Electron–Positron collider created 12 million Z^0s and the Stanford Linear Collider created half a million spin-polarized Z^0s.

For more than a decade, a coordinated worldwide research and development program has worked toward developing a TeV-scale electron–positron linear collider. At present, two preconceptual design proposals may be the contenders for future construction: the NLC, on which the U.S. and Japan are working to a common baseline design, and the TeV Energy Superconducting Linear Accelerator (TESLA), a European effort centered at DESY (Deutsches Elektronen–Synchrotron), the German high-energy physics laboratory.

The NLC is an electron–positron linear collider designed to begin



The Next Linear Collider Test Accelerator consists of a modulator to convert ac line power into dc pulses and klystrons that are driven by the dc pulses to produce radiofrequency power. The test accelerator also includes pulse compressors that reformat the radiofrequency output into 300-megawatt, 300-nanosecond-long pulses and accelerator structures that then use those pulses to establish the electromagnetic wave on which electrons surf.

operation at 0.5 TeV and ultimately be scaled up to 1.5 TeV. It will be 30 kilometers long and dominated by two opposing linear accelerators, or linacs. Although the NLC is based on mature technology, it still faces the big challenge of cost reduction. As SLAC physicist Marc Ross says, "Our mantra is 'Make it cheaper, make it cheaper, make it cheaper.'"

Van Bibber notes that the elements driving up costs are the tunnel—digging a 30-kilometer tunnel will be expensive—and the linacs themselves. "Luckily, the linac is a repetitive system. You're increasing energy, but not the speed of the particles, because they're already close to the speed of light. So what increases is the relativistic mass, which means we can be repetitive in the linac subsystems."

The basic linac has a modulator that converts ac line power—the same power one gets from a wall plug—into dc pulses to drive the klystrons (oscillators) that produce 75 megawatts of peak radiofrequency power at 11.4 gigahertz. Pulse compressors then reformat this radiofrequency output into 300-megawatt, 300-nanosecond-long pulses. The pulses are delivered to the accelerator structures, which establish the traveling electromagnetic wave on which the electrons surf.

"We're trying to build the linac for under $1 billion, even for as low as half a billion. That means we must get the subsystems down to $100 million each. The modulators and accelerator structures are where we, at the Lab, are focusing our efforts," says van Bibber.

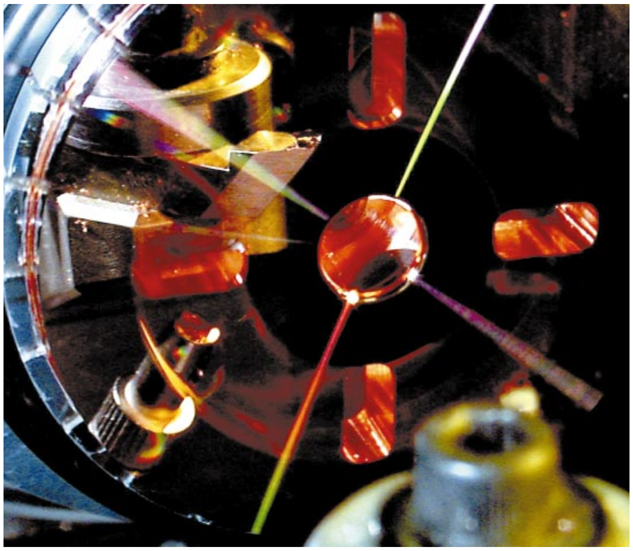
Modulating Power with Solid State

For the NLC, the modulator must be designed to keep costs down and still be efficient, reliable, and serviceable. Efficiency is a key criterion, notes Livermore engineer Ed Cook, who spearheads the effort to develop a modulator to fit the bill. "A 1-percent decrease in efficiency anywhere between the wall plug and the beam increases the required ac line power by a megawatt and adds a million dollars a year to the operating costs.” This small efficiency decrease would also have a ripple effect and increase the cost of components—from the modulator power supplies to the cooling systems required to remove the waste heat.

The new modulator for the NLC is based on solid-state technology that will provide significant improvement over previous equipment. Modulator efficiency is determined largely by the shape of the energy pulse produced. The ideal pulse shape is rectangular, because the energy in the pulse rise-time and fall-time is not usable. The waveform’s rise and fall in old-style modulators (hydrogen thyratron-fired pulse-forming networks, a technology dating from the 1940s) were less than precipitous, so energy was wasted. The advent of high-voltage and high-current solid-state switches—similar to those used in modern rapid transit systems—has made it possible to generate the required voltage pulses more efficiently. The goal is to have a rise-time and fall-time of less than 200 nanoseconds and a usable interval of more than 1.5 microseconds.

Designed as a modular part, the solid-state modulator can be pulled out and replaced easily, keeping maintenance costs down. The near-term goal is to design and make a prototype of a 500-kilovolt, 2,000-ampere modulator that will drive eight klystrons. The NLC will need about 400 of these modulators to drive its 3,200 klystrons.

The modulator is in the prototyping phase. Late in 1999, Livermore demonstrated a single modulator cell, consisting of a solid-state switch, a capacitor, and a transformer core, and delivered a five-cell stack to SLAC for measurement. “Results were good,” says Cook. “We were striving for 75-percent efficiency from the modulator, an improvement over the 60-percent efficiency of old-style modulators.”


About 200 copper cells—each differing slightly in its interior dimensions—are contained in each of the long tube structures in which the electrons and positrons are accelerated. The cells must be diamond-turned to tight tolerances and then precisely stacked and bonded together.

By spring this year, Bechtel Nevada—a key player on the Livermore team—will finish fabricating and assembling an additional 70 cells. Those, with the five already at SLAC, will comprise a complete modulator.

Accelerating down the Line

The NLC also will require between 5,000 and 10,000 structures—long tubes in which the beam flies in the machine—to accelerate the separate bunches of electrons and positrons to the interaction region. Each structure has about 200 precision copper cells. Each cell differs slightly from the others in its interior dimensions, with fabrication and alignment tolerances at the micrometer level.

Livermore, KEK, and SLAC worked together to build a 1.8-meter prototype structure. Livermore’s role was to develop a procedure for diamond-turning these cells to the required tolerance and to fabricate them. KEK stacked and diffusion-bonded the cells into a single copper structure, and SLAC completed and beam-tested the final assembly in June 1998.

“The structure is very unforgiving,” notes engineer Jeff Klingmann, Livermore’s contact for this work. “Each pulse contains 106 bunches of particles. The oscillating electromagnetic field pushes the bunches down the pipe at higher and higher energies. If one bunch wavers even a bit off center, it instigates an electrical field in its wake (a so-called wake field) that will affect the bunches following it and cause them to stray further off center. In short order, the beam fuzzes out and crashes into the cell walls. Our goals are to keep the beam very sharp, small, and straight and to develop a design that minimizes wake fields.”

The prototyping work highlighted two needs that must be addressed before cells can be manufactured in the millions: researchers must minimize the amount of diamond-turned machining, which is an expensive and time-consuming process, and they must design a cell assembly procedure that is automatically immune to alignment errors.

Klingmann says, “Our proposed new mechanical design reduces diamond-turning by 80 percent because our materials scientist John Elmer came up with a design in which only those surfaces that need to be completely smooth for bonding need to be diamond-turned. Our design also has interlocking features so each cell is necessarily aligned to its neighbor.”

The tolerances require precision machining and assembly, but cost pressures push the other way. As Elmer explains it, "The challenge is to make each one of these cells as cheap as a rollerskate wheel. We're looking at each step in the manufacturing and assembly process to cut costs. Casting in a vacuum means we get less porosity, but that costs $50 per cast. We need to get the cost down to $5." Elmer has also been examining cost-efficient ways to bond the cells together.

Improving Positron Targets

Creating beams of positrons turns out to be a difficult problem. As Livermore engineer Charlie Landram explains, "Positrons don't exist naturally. They're produced by crashing a high-energy electron beam onto a target—in this case, made of a tungsten–rhenium alloy. The result is a low-energy shower of electrons, gamma rays, and positrons. The positrons are captured and boosted in energy, then injected into a damping ring to cool the beam down, allowing it to be squeezed into a tiny cross-sectional area."

The targets that are planned for the NLC are similar to those currently being used at the Stanford Linear Collider, where a recently removed target showed damage more serious than expected. This postmortem discovery brought the NLC positron target issue to the fore, because the NLC target must produce more than 20 times the number of positrons and handle power about 10 times higher than Stanford's. Livermore scientists modeled the Stanford target using Monte Carlo particle codes and thermohydraulic models, while Los Alamos National Laboratory scientists evaluated the damaged target.

"All our calculations show us to be just below the critical heat flux, which means there is very little margin to avoid a burnout condition. We're looking at ways to keep future targets from reaching these fluxes under more extreme conditions," says Landram. "Right now, we're considering a target with a larger radius, which could accommodate the extra heat, and improved heat paths to the cooling tubes. We're still examining the damage to the Stanford Linear Collider target and considering the best ways to carry off the heat. We need a better handle on what the experiments are doing to the target so we don't encounter problems in the NLC."

One Success Encourages Another

The NLC builds on the success of the B Factory (see *S&TR*, January/February 1999, pp. 12–14, and *S&TR*, January/February 1997, pp. 4–13). Van Bibber says, "With the B Factory, the collaboration delivered on time and on budget. The machine now holds the world's record for electron–positron luminosity and is still improving. The DOE uses that three-lab partnership as a model for future major facility acquisitions."

These two projects are part of a long line of efforts that include the BaBar detector at SLAC, Brookhaven National Laboratory's PHENIX detector, proton radiography and the Scrounge-atron proton accelerator, the Rare Isotope Accelerator, the Spallation Neutron Source, the Accelerator Production of Tritium, and the Accelerator Transmutation of Waste. The B Factory and the NLC are just the latest accelerator science and technology efforts in which Lawrence Livermore has been involved. Whether performed within Livermore or in partnership with other laboratories in the U.S., this work leverages the Laboratory's strengths in accelerator physics, detectors, engineering, and physics to add value to the nation's accelerator efforts.

—Ann Parker

Key Words: accelerator structure, electron–positron linear collider, high-energy particle accelerator, Next Linear Collider (NLC), positron target, proton collider, solid-state modulator, Stanford Linear Accelerator Center (SLAC), Tevatron.

For further information contact Karl van Bibber (925) 423-8949 kvanbibber@llnl.gov.

About the Scientist

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 Directorate. He was recently the project leader for Livermore's work on the B Factory at the Stanford Linear Accelerator Center and is currently the leader of Lawrence Livermore's contributions to the Next Linear Collider collaboration.