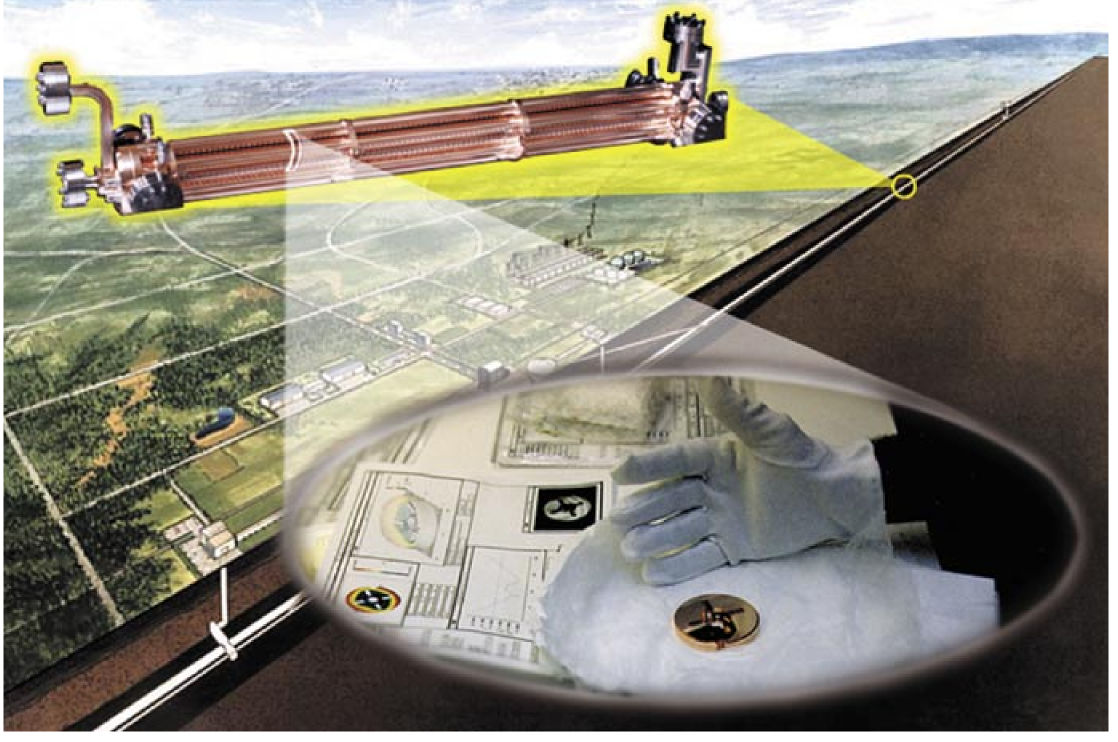
Solid-State Technology Meets Collider Challenge

PROBING the frontiers of particle physics and delving into the mysteries of the universe and its beginnings require machines that can accelerate beams of fundamental particles to very high energies and then collide those beams together, producing a multitude of exotic subatomic particles.

The proposed Next Linear Collider (NLC), being developed by Stanford Linear Accelerator Center (SLAC), Lawrence Livermore and Lawrence Berkeley national laboratories, and Fermi National Accelerator Laboratory (Fermilab), is such a machine. The NLC is expected to produce a variety of subatomic particles by smashing together electrons and their antimatter counterparts (positrons) at nearly the speed of light with energies in the teraelectronvolt (TeV) range.

Plans are that the NLC will initially operate at 0.5 TeV and ultimately be scaled up to 1.5 TeV. (See *S&TR*, April 2000, pp. 12–16.) Work at the facility will complement the research to be conducted at another high-energy particle accelerator, the 14-TeV Large Hadron Collider at the European Laboratory for Particle Physics (commonly known by the acronym CERN from its former name) in Geneva, which is scheduled for completion in 2007.

Achieving beam energy levels in the TeV range requires modulator systems that can convert ac line power—the same type of power one gets from the wall plug—into dc pulses. Ultimately, these pulses are transformed into radiofrequency (rf) pulses that "kick" the particles up to the required energy levels. Livermore scientists and engineers have designed a solid-state modulator to replace old-style modulators based on vacuum-tube technology. These new modulators promise to be far more efficient, reliable, and serviceable than the previous components. Livermore's Laboratory Directed Research and Development Program supported the basic research and development on the solid-state modulator technology, and SLAC supported the systems integration.



A conceptual drawing of the Next Linear Collider, housed in a tunnel approximately 30 kilometers long, inside of which are two opposing linear accelerators (linacs). Within each linac, the electrons (or positrons) are accelerated inside thousands of copper accelerator structures, each made up of more than 200 precision-machined copper cells (see inset).

Reprinted from Science & Technology Review, September 2004

UCRL-TR-215579

Start of the Power Train

The NLC will accelerate a beam of electrons and a beam of positrons down two opposing 15-kilometer linear accelerators, or linacs. Each linac is a repetitive system with pulses identical in energy level and wave shape generated at the rate of 120 pulses per second.

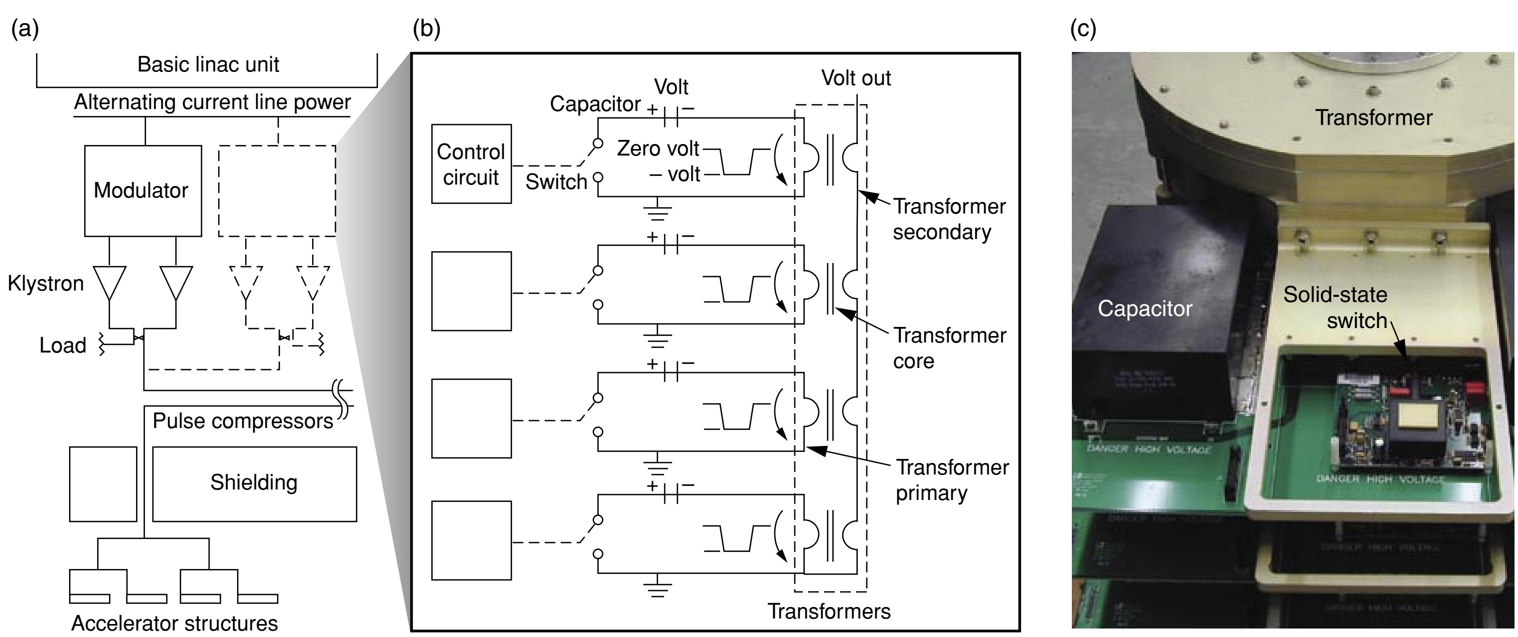
The basic linac consists of a modulator to convert ac line power into dc pulses and klystrons (oscillators) that are driven by the dc pulses to produce 75 megawatts of peak rf power at 11.4 gigahertz. The linac also includes pulse compressors that reformat the rf output into 300-megawatt, 300-nanosecond-long pulses. These pulses are then delivered to accelerator structures constructed of copper disks. The electron and positron particle beams surf the pulses as they travel through these disks, gaining energy as they pass from one accelerator structure to the next. The NLC is an order of magnitude larger in size than any other linear accelerator yet designed and will have between 5,000 and 10,000 accelerator structures.

Modulating Power with Solid State

When Livermore engineers began the modulator design for the NLC, they revisited the possibility of creating a solid-state system. The old-style modulators based on hydrogen thyratron-fired pulse-forming networks (PFNs), a technology dating from the 1940s, have some definite drawbacks for a system the size of the NLC. For example, a thyratron-switched PFN can drive only a single 75-megawatt klystron and has an operational lifetime of 2 years or less before requiring replacement. Engineer Ed Cook notes that few vendors exist today who make thyratron switches. “Fabricating these switches is a bit of a black art. It requires a lot of manual expertise, and that expertise is disappearing. For a long time, we’ve wanted to replace these vacuum-tube switches with solid-state switches.”

The biggest obstacle has been that, until fairly recently, solid-state switches couldn’t handle high voltages. Thyratron switches can withstand the high voltages used in high-energy physics experiments and can easily reach 100 kilovolts. However, 6.5 kilovolts was the limit for a solid-state switch that could be turned on and off with a gate control signal, and the NLC requires a 500-kilovolt pulse. Livermore came up with a design capable of withstanding this voltage level using a series of solid-state switches buffered with a transformer.

The solid-state modulator’s efficiency is vastly improved over thyratron-based modulators. The shape of the modulator’s energy pulse largely determines its efficiency. The ideal pulse shape is rectangular because the energy in the pulse’s rise and fall time is not usable by the klystron to generate rf power. For the NLC, the goal is to have a rise and fall time of less than 200 nanoseconds, which is difficult to obtain with a PFN modulator using thyratrons. The performance of a solid-state modulator based on an inductive adder circuit topology has the potential for a sharper rise and fall time than the thyratron-based modulator, yielding a pulse with less

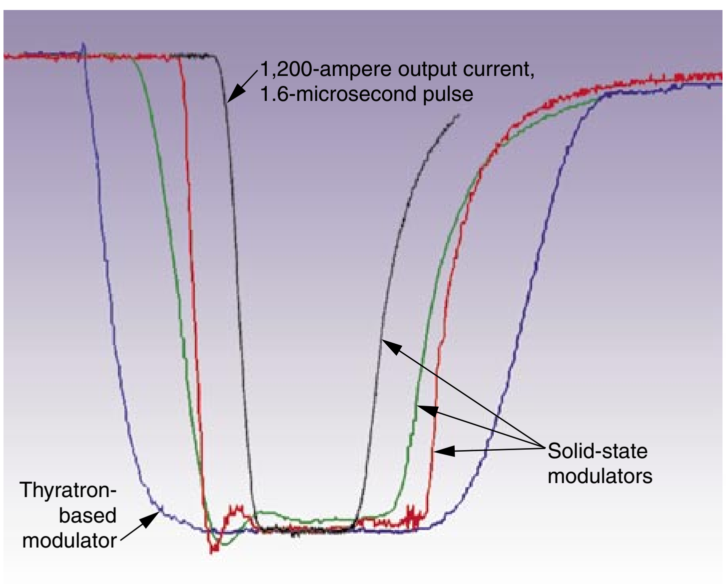


(a) The Next Linear Collider being developed by the Stanford Linear Accelerator Center and other labortories will consist of thousands of basic linear accelerator (linac) units. Each unit consists of modulators, klystrons, pulse compressors, and accelerator structures. (b) This schematic shows a four-cell stack of the Livermore-designed modulators based on solid-state switch technology. (c) A close-up view of the modulator shows a solid-state switch, a capacitor, and a transformer core.

wasted energy. The pulse duration can also be easily lengthened or shortened.

The modulator's switch—called an insulated gate bipolar transistor (IGBT)—is available from many manufacturers and can operate in environments that make them useful to the NLC. "They're similar to those used in modern rapid transit systems," says Cook. "The technology has advanced to the point where they can be used in a high-current, high-voltage environment."

Each modulator cell consists of two major components: a drive board formed from two circuit boards, each holding a solid-state switch and a capacitor, and a tightly coupled pulse transformer. A solid-state switch can generate a 4-kilovolt, 6-kiloampere pulse; 12 modulator cells can collectively yield a pulse of approximately 50 kilovolts. If a modulator cell needs servicing, a board can easily be pulled and replaced. "We'll need 1,000 modulators, each consisting of 15 cells, to drive 2,000 klystrons for the NLC," says Livermore physicist Jeff Gronberg. "We're looking at nearly 30,000 boards in all, so reliability and ease of maintenance are very important." The plan is to have redundant boards and then switch to the backup board if one goes bad, a much less painful process than replacing a failed thyratron. "When a thyratron fails, a section of the linac goes down with it," says Gronberg. "It can take the better part of a day to replace it and have the system running again."



Modulator efficiency is determined largely by the shape of the energy pulse produced. The new solid-state modulator yields more useful energy per pulse using either Mitsubishi (green and black waveforms) or Eupec (red waveform) insulated gate bipolar transistors (IGBTs), as shown by the far steeper rise and fall times, than the old-style modulator using hydrogen thyratron-fired pulse-forming networks (blue waveform).

Testing the System

Last year, Livermore delivered the first full-power prototype modulator consisting of 15 cells. The Livermore team and the Power Conversion Group at SLAC are conducting tests on the entire rf system using the solid-state modulators and a new 500-kilovolt, 75-megawatt klystron.

"We're testing each component of the basic linac unit—modulator, klystron, pulse compressor, and accelerator structure—to demonstrate its reliability and performance," says Gronberg. "Reliability is critical. Once the NLC is up and running, it will be on line 24 hours a day, 7 days a week, 9 months a year. Now, with the solid-state modulator, the loss of one or two boards in any given modulator will not affect the accelerator's operation. Routine maintenance can be performed at scheduled down times. Previously, we would have had to maintain 2,000 vacuum-tube thyratron switches for the entire collider. Given the failure rate of the vacuum tubes, we would have been repairing on average one per day."

The modulator prototype recently achieved its design parameters, producing 1.6-microsecond pulses of 500 kilovolts with a 120-hertz repetition rate. "The Laboratory's investment in the modulator project is now paying off in dividends," says Gronberg. "Using this technology will save about $200 million on the cost of the NLC. The benefits are also accruing in other accelerator projects and in pulse-power applications, such as Pockels cell drivers for high-power lasers. Once a new technology is demonstrated, people often find other applications where it can make a difference."

—Ann Parker

Key Words: electron–positron linear collider, Next Linear Collider (NLC), klystron, particle accelerator, solid-state modulator, Stanford Linear Accelerator Center (SLAC), thyratron, vacuum-tube technology.

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This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.