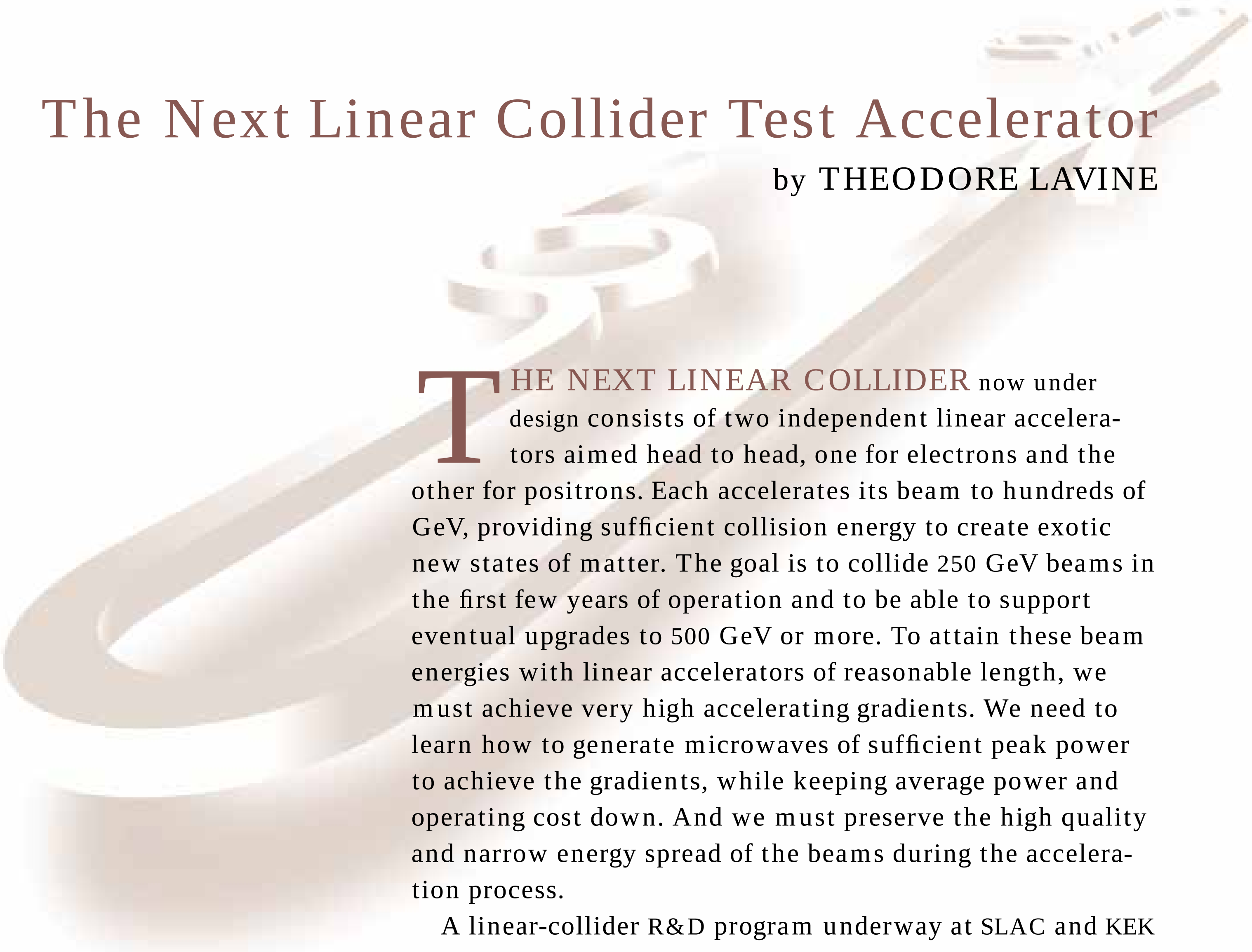


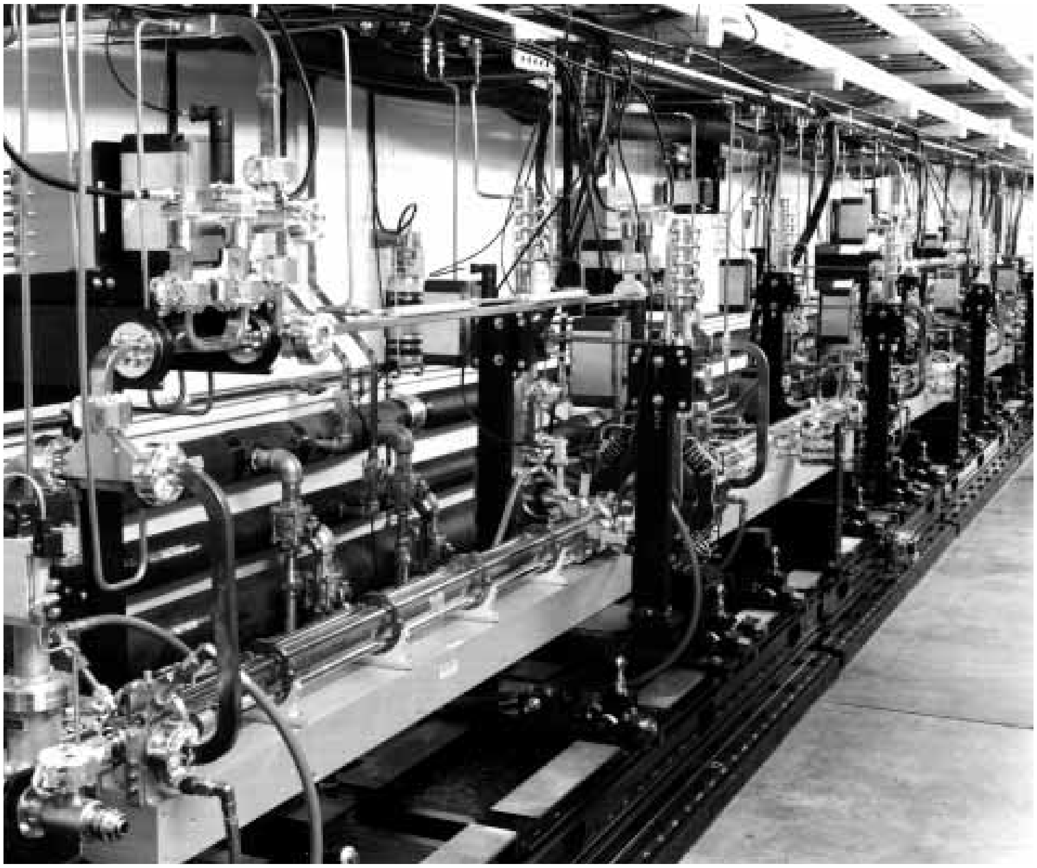
The Next Linear Collider Test Accelerator

by THEODORE LAVINE

THE NEXT LINEAR COLLIDER now under design consists of two independent linear accelerators aimed head to head, one for electrons and the other for positrons. Each accelerates its beam to hundreds of GeV, providing sufficient collision energy to create exotic new states of matter. The goal is to collide 250 GeV beams in the first few years of operation and to be able to support eventual upgrades to 500 GeV or more. To attain these beam energies with linear accelerators of reasonable length, we must achieve very high accelerating gradients. We need to learn how to generate microwaves of sufficient peak power to achieve the gradients, while keeping average power and operating cost down. And we must preserve the high quality and narrow energy spread of the beams during the acceleration process.

A linear-collider R&D program underway at SLAC and KEK has developed a new generation of microwave power sources and high-gradient accelerators equal to these tasks. As part of this program, the Next Linear Collider Test Accelerator (NLCTA) has been operating at SLAC since 1996 as a full-system test bed for these technologies. NLCTA is a high-gradient linear accelerator (linac) with its own dedicated electron injector. The accelerator structures and the microwave power systems that energize them are engineering prototypes for the linacs of a full-scale collider.

The forefather of the NLCTA linac is the three-kilometer-long SLAC linac, built in the early 1960s utilizing the 10.5 cm wavelength (S-band) klystron amplifiers and accelerator



The NLCTA linac currently has four 180 cm long accelerator structures installed between focusing magnets.

structures developed at Stanford during the 1940s and 1950s. Improvements in the klystrons powering the linac led to a continuous series of upgrades from the original, 24 megawatt (MW) tubes to 67 MW tubes developed in the 1980s—boosting the SLAC beam energy from 16 GeV in 1966 to 50 GeV today.

For the Next Linear Collider (NLC), accelerator designers have elected to use an X-band wavelength of 2.6 cm. The accelerator structures in the NLCTA are prototypes developed specifically for this shorter wavelength, which boosts the achievable gradient and reduces the cross-sectional area of the accelerator structure. The shorter wavelength also lowers the microwave filling time of the structure from 1 microsecond to 0.1 microsecond, reducing the needed microwave pulse length. While the SLAC linac achieves a gradient of 20 million volts per meter (20 MV/m), the NLC linacs will reach 50 MV/m for the same average electric power consumption (about 10 kW per meter of accelerator) at 120 pulses per second.

But many of the technical challenges for building the new accelerator and its power sources grow with the gradient because higher peak power is needed. The SLAC linac requires peak power of about 12 MW per meter of structure, while the NLCTA requires 50 MW per meter to achieve a gradient of 50 MV/m—or 100 MW/m to achieve 70 MV/m.

MAKING THE GRADIENT

The X-band klystrons for the NLCTA are the result of a decade of R&D on high-power klystron technology at SLAC. Each klystron generates 50 MW pulses of microwave radiation. As presently configured, the NLCTA operates with three 50 MW klystrons, each of which energizes a pair of accelerator structures. The energy in each klystron pulse is compressed to produce the full 200 MW required to achieve the 50 MV/m gradient in the pair.

The primary technical challenge of pulse compression is storing the microwave energy with low loss for the duration of the klystron pulse. The solution developed in the 1970s to boost peak power in the SLAC linac was to store the energy in oversized, cylindrical copper cavities. A major difference in the NLCTA is that the shorter microwave pulse length now makes it possible to use extended microwave transmission lines for low-loss energy storage. After the klystrons shut off, each storage line continues to discharge its pulse until the last part of the wave has traversed the entire line.

With higher peak power comes the challenge of handling stronger electromagnetic fields in the waveguides and other components that supply power to the accelerator structure. The NLCTA components are able to handle the peak power as a result of years of careful microwave engineering design and testing. Initial prototypes that suffered from electrical breakdown were redesigned to reduce the field strengths.

The accelerator structures were developed jointly by SLAC and KEK. Considerable attention went into copper-processing and machining techniques needed to achieve clean, smooth surfaces capable of sustaining high field gradients without emitting stray electron currents that can disturb the primary beam. Even after fabrication and installation, the internal surfaces of the structures must be conditioned by an aggressive regimen of high-power microwave processing to reduce surface emission.

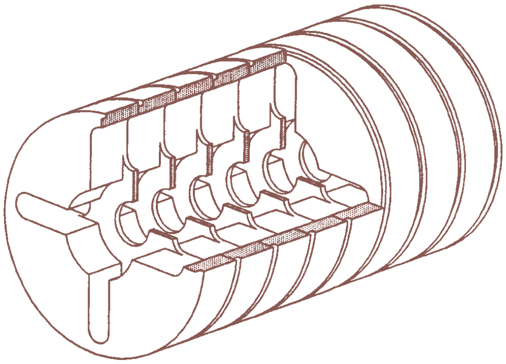
In 1997 we achieved the primary goal for the NLCTA power system: the NLCTA linac operated stably at the design gradient of 50 MV/m with tolerable electron emission. The maximum beam energy at this gradient (with four 180 cm structures and two 90 cm structures installed) is 450 MeV. The achievable energy at the design current is only 350 MeV because of beam loading.

Our next goals are to generate and test stable accelerating gradients up to 70 MV/m, which requires twice as much peak power. The first steps of this program are complete. A single 50 MW klystron (and pulse compressor) has been used to push the accelerating gradient in a single structure (not a pair) to 70 MV/m, and one of the klystrons has been operated at 75 MW (by increasing its high voltage). The next steps will be to use two klystrons to generate the 70 MV/m gradient simultaneously in a pair of structures and to test the stability of acceleration in that configuration.

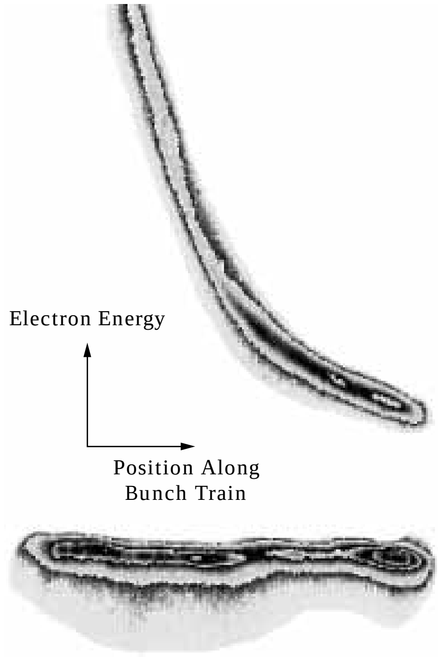
BUNCH TRAINS

In order to accelerate enough current on each machine pulse to create the event rates required for high-energy physics experiments, the NLC will accelerate a long train of 100 bunches, rather than a single bunch, on each microwave pulse. A challenge that designers face is the transverse instability that arises because a bunch can be deflected by the electromagnetic fields (wake fields) created by slight but inevitable offsets of preceding bunches from the central axis of the accelerator. The small size of the accelerator apertures for the 2.6-cm wavelength exacerbates this problem.

All the NLCTA structures are designed to suppress these wake fields by varying, in a precise pattern, the internal dimensions of the 200 cells that comprise a 180 cm structure; this spoils the coherence of the set of microwave modes that would otherwise contribute to the wakefield. The diameters of the irises in such a "detuned" structure vary from 8 to 11 mm. Two of the structures further suppress beam deflection by damping the undesirable modes by channeling them through slots that lead to microwave absorbers. Joint work at SLAC and KEK has developed the design techniques and manufacturing methods necessary to achieve



Cutaway view of part of a damped and detuned accelerator structure (top). The structure is fabricated from a stack of cells similar to the one shown above.



Digitized images of NLCTA beam spots showing the energy variations along the train of electron bunches. The images show the correlation of electron energy with position along the 36 meter long train. When the microwave pulses are not modulated (upper image), the electron energy drops off along the train by about 15 percent, approaching an equilibrium value that corresponds to steady-state beam loading. But when the microwave pulses are modulated to compensate for the transient beam loading (lower image), the energies of the electrons along the entire train are uniform to withn a few tenths of a percent.

the close tolerances needed for these damped and detuned structures.

The NLCTA injector makes trains of 1400 electron bunches spaced 2.6 cm apart. The strategies of detuning and damping have worked, for without them the accelerator structures could not transmit these trains. The future NLC injectors will probably distribute the same total charge into one-eighth as many bunches, spaced eight times further apart. Nevertheless, based on the stability of bunch trains in the NLCTA, we can predict stability in the NLC because the deflecting forces are proportional to the ratio of bunch charge to spacing, which will be the same.

Uniform acceleration of all the bunches in each train is required because only electrons and positrons within a narrow energy range (tenths of a percent wide) can be focused at the collision point. One of the most significant tests completed on the NLCTA has been to show that the bunch-to-bunch variation of energy along the train can be kept this small. This is a significant issue since, under the wrong conditions, the leading bunches in a train can extract too much microwave energy from the accelerator structure, and the trailing bunches will come up short. One strategy for achieving uniform acceleration is to fill the structure with microwave energy in a profile that matches what would occur behind an infinitely long train, so that all the bunches that follow get the same acceleration. The desired profile has been obtained by modulating the microwave pulses before the klystrons amplify them. With this approach, the energies of the electrons along the entire bunch train come out the same within a few tenths of a percent, as desired.

There are other potential applications for the NLCTA. A group at the Stanford Synchrotron Radiation Laboratory and SLAC has considered modifying the NLCTA to drive an X-ray free-electron laser into self-amplified spontaneous emission. The NLCTA can also be used to generate 2.6 cm microwaves or higher harmonics by decelerating the beam in resonant cavities or structures inserted in the beam line. Physicists from Harvard and SLAC are using the beam to excite 3.3 mm waves (the eighth harmonic of 2.6 cm) in a cavity with an aperture 1 mm in diameter. In future experiments, they plan to use a structure 25 mm long to excite 3.3 mm waves at multi-megawatt peak power levels and use them to generate accelerating gradients perhaps greater than 100 MV/m. Such high gradients are possible at these short wavelengths, but they raise the challenges of power levels, field strengths, and instabilities to new heights. These experiments with short, 3.3 mm wave structures will test advanced concepts for accelerators in the era beyond the NLC.

The experience gained by operating the NLCTA has been critical for understanding the performance and reliability of the complete systems of power sources, microwave components, and structures to be used in the NLC linacs. Future modification will continue to test new prototype components. Other applications as an experimental tool for studying accelerator and beam physics are only beginning to be exploited.