International Collaboration on Linear Collider Research and Development

by GREGORY LOEW & MICHAEL RIORDAN

Physicists around the globe are cooperating on designs for a trillion-volt linear collider.

SINCE THE MID-1980s a growing international collaboration of high energy physics laboratories and other institutions has been doing extensive research and development toward the design and construction of a TeV-scale linear electron-positron collider. The particle physics community has been interested for years in building such a collider, which would fire tiny bunches of electrons and positrons at each other with combined energies between 0.5 and 1.5 trillion electron volts. This interest intensified with the recent decision by the European Laboratory for Particle Physics (CERN) to proceed with the Large Hadron Collider. Indeed, these two machines can make highly complementary contributions to our understanding of elementary particles.

Such a TeV linear collider can serve many functions. It will be a precision tool to study production and decays of the massive top quark. If the Higgs boson (or bosons) and supersymmetric particles exist, it should be instrumental in fostering their discovery and further study. If they do not, such a collider will allow the exploration of other mechanisms being proposed for electroweak symmetry breaking, which is thought to imbue elementary particles with their widely differing masses. These are several of the burning physics questions that need to be elucidated during the coming decade.

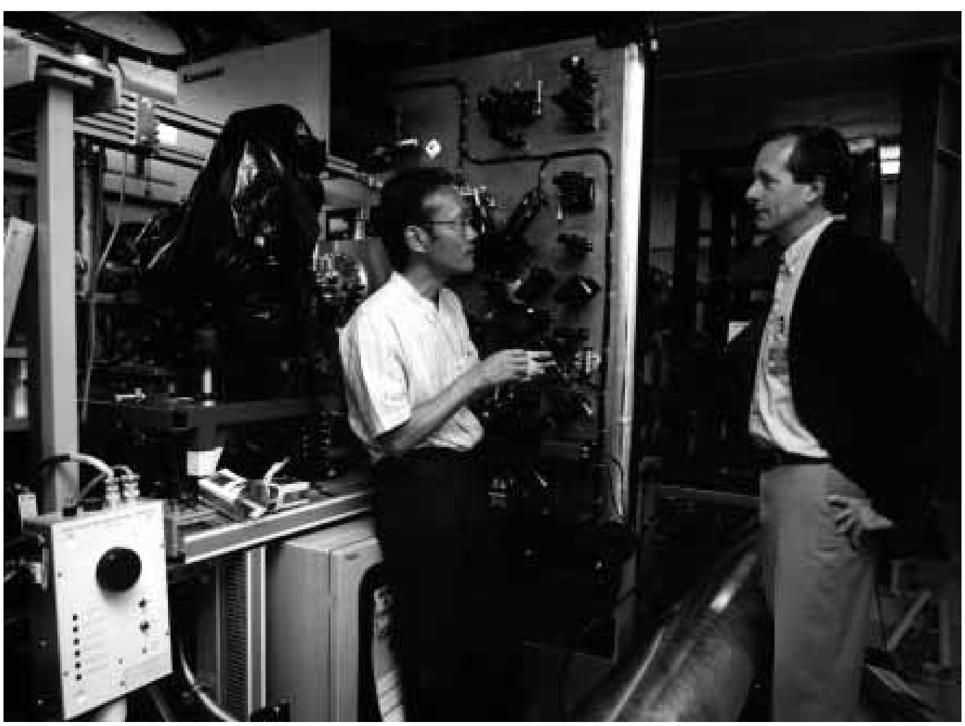
In addition, a TeV linear collider will provide exciting physics research opportunities based on high energy electron-electron, electron-photon and photon-photon collisions. Other applications, such as free-electron lasers for the study of matter at atomic dimensions, are also possible.

MOTIVATED BY the late 1980s startup of the SLAC Linear Collider and the possiblity of extending this technology to higher energies, a nucleus of institutions began doing collaborative R&D in this field. At first, this effort was fairly informal, resulting in small one-on-one joint investigations. During the 1990s, it gradually evolved into larger projects such as the 300 meter Final Focus Test Beam at the Stanford Linear Accelerator Center. The principal goal of this roughly $20 million project was to study the design and operation of a state-of-the-art magnet array required to generate the exceedingly narrow, ribbon-like electron and positron beams needed at the interaction point of a TeV linear collider.

Groups from the German Electron Synchrotron (DESY) in Hamburg; the Max Planck Institute in Munich; the Linear Accelerator Laboratory (LAL) in France; the National Laboratory for High Energy Physics (KEK) in Japan; the Budker Institute of Nuclear Physics (BINP) in Novosibirsk, Russia; the Fermi National Accelerator Laboratory in Batavia, Illinois; and SLAC joined forces to build this facility. The Russians fabricated almost all of the forty precision dipole, quadrupole, and sextupole magnets that serve as "optical" elements in what is essentially the world's biggest "compound lens." The last two quadrupoles, which were manufactured by Japanese industry under the direction of KEK physicists, have pole faces machined to micron accuracies. DESY physicists supplied a high-precision alignment system to guarantee that components of this complex magnet array remain in their designated positions. And KEK and LAL built monitors to measure the transverse dimensions of the electron bunches at the focal point—one based on Compton scattering of photons (see photograph at left) and the other on ions scattered from gas jets.

Experiments at SLAC have produced electron beams that are only 120 nanometers high (a typical virus is about 100 nm across), in good agreement with predictions. That's an extraordinary vertical compression factor of over 300 on the initial 50 GeV beam supplied by the SLAC linear accelerator. This level of demagnification already exceeds what is required for TeV linear colliders. What's more, the Final Focus Test Beam has demonstrated that such flat, narrow beams can indeed be controlled and monitored, which was not at all obvious when this project began construction.

Tsumoru Shintake and David Burke with the laser beam monitor built by KEK for the Final Focus Test Beam at SLAC.



IN EARLY 1987, at a meeting of the International Committee on Future Accelerators (ICFA), SLAC Director Burton Richter had suggested that all groups doing research on linear colliders start working together more cohesively. In 1988 the community began holding two series of regular workshops around the world—one (labeled "LC") to review and compare the various design alternatives for a large linear collider, and the other to discuss the physics potential of such a machine. During LC93 at Stanford, DESY, KEK, and SLAC exchanged an informal memorandum of understanding to establish an international collaboration whose main purpose was to pursue linear collider R&D cooperatively. The collaboration's primary objectives, according to David Burke and Richter, was "to enhance the exchange of personnel between participating institutions, to promote coordination in planning and sharing of research facilities, and to provide a mechanism for all interested parties to participate in the evaluation of the alternative technological approaches that are presently being pursued."

That agreement established a Collaboration Council, whose first formal meeting occurred in July 1994 at the European Particle Accelerator Conference in London. The Council, in turn, set up a Technical Review Committee (TRC) whose specific charge was to examine and compare the various accelerator technologies and designs that might be suitable for a linear collider with an initial center-of-mass energy of 500 GeV and a luminosity in excess of 10^{33}cm^{-2} sec^{-1}, which could be expanded to at least 1 TeV with roughly five times higher luminosity.

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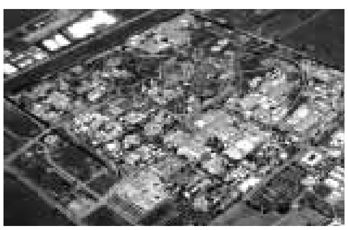
The TRC consisted of more than 50 scientists from 17 institutions around the globe. Meeting and corresponding over the following year and a half, they produced and published a comprehensive R&D report that was distributed to the community in January 1996. This document presents descriptions of all linear-collider designs so far proposed, comparative reviews of major subsystems, descriptions of relevant test facilities and experiments done on them, plus the potential of the various designs for being upgraded to higher energies. The report lists present and possible future areas of collaboration. It concludes that "the diversity of projects and test facilities we have created somewhat spontaneously throughout the world community is a good hedge against mistakes, and . . . it is producing a broad body of knowledge that benefits all of the projects." The TRC report is available on the World Wide Web at www.slac.stanford. edu/xorg/ilc-trc/ilc-trchome.html; essential parts of it, including progress reports and tables of major linear-collider design parameters are updated about twice a year.

AFTER NEARLY a decade of international collaboration on linear collider R&D, where does the community stand today? Five major new test facilities have recently begun operation. These include two model test accelerators at DESY, one each at SLAC and CERN, plus an advanced storage-ring facility at KEK whose goal is to study the preparation of narrow, ribbon-like beams to be injected into such linacs. As a result of this and other research, the status of the four principal categories of linear-collider designs (see top table on page 38) is becoming better understood.

Although the parameters and technologies of the main linacs in these design categories differ substantially (see bottom table on page 38), the machines share many common features and problems. To reach the desired luminosity, for example, all approaches (except the Russian VLEPP design) accelerate many electron or positron bunches in each pulse of microwave radiation. But launching such long sequences of closely spaced bunches means that the electromagnetic fields generated in the wake of each bunch—its so-called wakefields—can deflect the following bunches up, down, or sideways. This troublesome effect can make it difficult to maintain the extremely narrow, flat electron and positron beams needed at the interaction point to attain high collision rates. Thus all linear-collider designs (except VLEPP) use techniques to



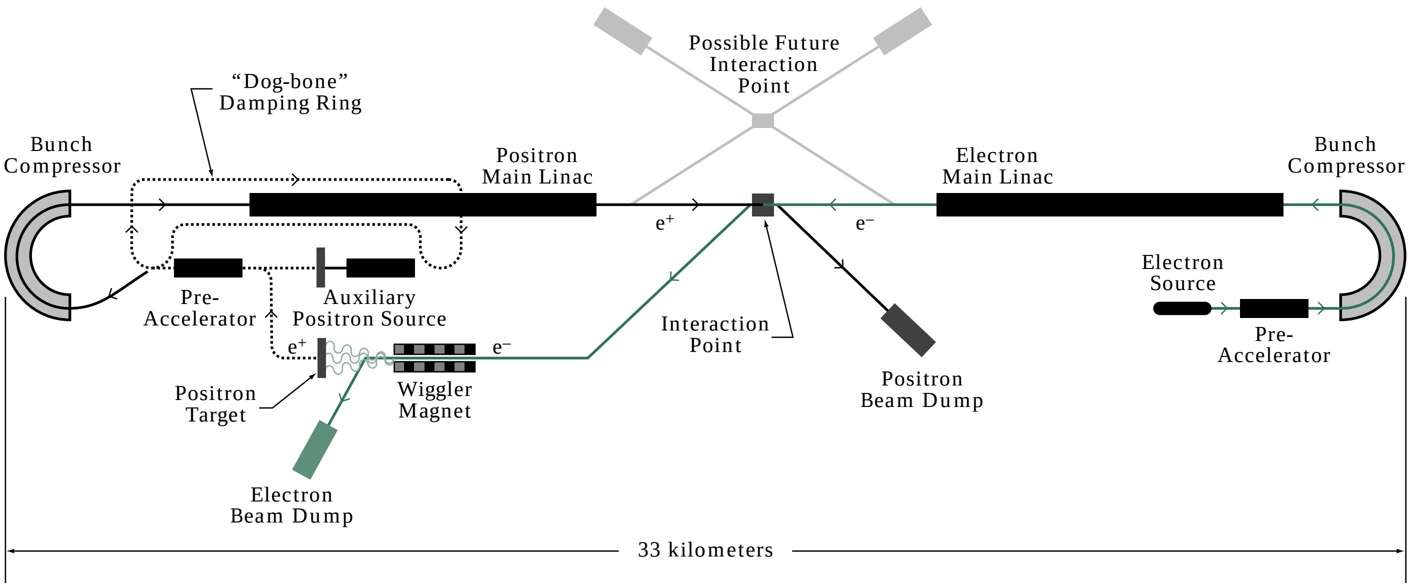
Linear Collider World Picture

Collider Design	"Hub" Laboratories	Corresponding Test Facilities
TESLA	DESY	TESLA Test Facility
SBLC	DESY	S-Band Test Facility
JLC(C)	KEK	Microwave Systems
JLC(X)	KEK	Accelerator Test Facility
NLC(X)	SLAC	SLC, FFTB, NLC Test Accelerator
	LBNL, LLNL	Relativistic Two-Accelerator Test Facility
VLEPP(J)	BINP	VLEPP Test Facility
CLIC	CERN	CLIC Test Facility

Parameters for a Linear Collider with a Total Energy of 500 GeV

	TESLA	SBLC	JLC(C)	JLC(X)	NLC	VLEPP	CLIC
Main linac frequency (GHz)	1.3	3	5.6	11.4	11.4	14	30
Luminosity $(cm^{-2}s^{-1}) \times 10^{33}$	6	5.3	7.2	6.1	5.3	9.7	4.9
Beam height at final focus[a] (nm)	38	30	8.6	6.2	12.2	8	10.8
Accelerating Gradient (MV/m)	25	17	33	56	55	78	100
Number of klystrons	616	2517	4184	4400	3030	1400	2 drive linacs
Number of bunches/second	5650	16650	7200	12750	9720	300	30,000

[a]The beam height given here is twice the rms vertical beam dimension σ_y* generally quoted in technical literature.



Layout of the proposed TESLA linear collider, which employs superconducting accelerating cavities in both main linacs.

suppress these wakefields before they cause serious damage to beam quality.

Other features common to all four design categories include particle injectors; damping rings; alignment systems; ground-vibration suppressors; vacuum systems; feedback, instrumentation and control systems; beam delivery systems; and final-focus systems—as well as much of the civil engineering and electromechanical infrastructure. In all of these areas, valuable cross-fertilization and collaboration occurs among the various groups, which benefit from reviews that take place at the regularly scheduled LC workshops.

HEADQUARTERED AT DESY, the TESLA collaboration involves 22 institutions spanning the globe from Beijing through Warsaw and Paris all the way to Los Angeles. This team has designed the only machine that uses superconducting accelerating cavities for the main linacs (see diagram above). With microwave power at 1.3 GHz accelerating 5650 bunches per second, it has the greatest time lag between bunches (708 nanoseconds), the lowest transverse wakefields and thus the loosest alignment tolerances. Other special features include a long "dog-bone" shaped damping ring and a positron-production system that uses gamma rays generated by passing the primary electron beam through a wiggler magnet.

The new TESLA Test Facility is being assembled in successive steps through the addition of cryomodules that contain the superconducting cavities. It has already generated a 125 MeV electron beam, and in the next few years it will be extended to incorporate a free-electron laser. Physicists and engineers building this test facility have so far achieved an accelerating gradient of 16 million volts per meter (or 16 MV/m) and are making good progress toward their design goal of 25 MV/m. Their greatest challenge is to develop techniques to turn these encouraging results into a reliable and affordable technology.

The S-band Linear Collider (SBLC) proposed by DESY physicists as a TESLA backup takes advantage of the most widespread and proven microwave technology—the 3 GHz S-band technology used for decades at Stanford and elsewhere. Taken together, its two "conventional" linacs are roughly equivalent to ten SLAC linacs and would stretch about 30 kilometers in all. After TESLA, the SBLC has the next-largest beam height at the final focus. It would operate at 50 microwave pulses per second with 333 bunches per pulse spaced 6 nanoseconds apart. Because

KEK and SLAC physicists who recently performed experiments at KEK's Accelerator Test Facility.

of this multibunch operation, its accelerating structures have been designed to detune and damp most transverse wakefields by using two sets of higher-order mode couplers in each section whose signals can also be used for alignment purposes. Initial tolerances are about 100 microns, and the sections must eventually be aligned to within 30 microns. Prototypes of the 150 megawatt (peak power) klystrons needed by the SBLC have been developed at SLAC as part of a bilateral collaboration with DESY.

In the original TRC report, the C-band Japan Linear Collider, or JLC(C), was not considered in detail because experimental work on it at KEK had not yet begun. Since then an active R&D program has been started on its microwave components, including a 50 megawatt klystron and an ingenious 1.8 m accelerator structure that lets the undesirable transverse wakefields leak out while keeping the longitudinal, accelerating mode "choked" inside the cavity. This choke-mode structure eliminates wakefield problems and has an alignment tolerance of 30 microns. The JLC(C) beam characteristics are similar to those of the X-band designs (see below), except for a longer bunch length.

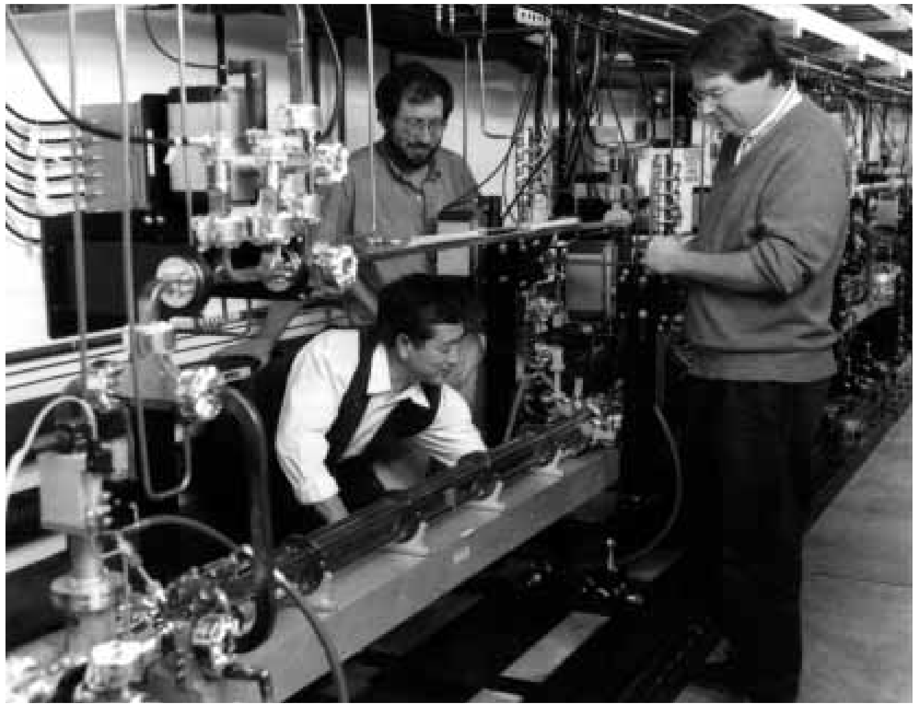
The X-band Japan Linear Collider, or JLC(X), and the SLAC-designed Next Linear Collider, or NLC, both use 11.4 GHz microwave power for their main linacs. They have similar pulse repetition rates, numbers of bunches per pulse, particles per bunch, and peak luminosities. The different beam heights at the interaction point do not arise from any fundamental design differences. As the cooperation between KEK and SLAC matures, this and other remaining differences will likely shrink —a process that has already occurred in the design of the accelerator structures. The NLC currently uses accelerator sections in which transverse wakefields are detuned and damped by coupling these modes to external manifolds and loads. The latest sections of this type have been machined at Lawrence Livermore National Laboratory (LLNL), cleaned at SLAC, diffusion bonded in Japan, and returned to SLAC for final brazing. Tests of these sections have begun on the Next Linear Collider Test Accelerator facility at SLAC (see photograph on the next page).

Microwave power for the NLC will be supplied by 75 megawatt X-band klystrons that use permanent magnets to focus the stream of low-energy electrons traveling through each klystron tube. This energy-saving innovation has recently been successfully tested at SLAC. Similar klystrons will likely be used in the JLC(X) design. To increase the peak power levels, both machines will probably use the delay-line distribution system proposed by KEK physicists to combine the microwave pulses from several klystrons and distribute slices of the resulting pulse to individual accelerator sections. Because much of the cost of these

X-band collider designs comes in the manufacture of their klystrons and the modulators that supply them with electrical power, there are substantial R&D efforts under way to reduce these costs and attain high power-conversion efficiency.

The trains of electron bunches for both machines will be generated by laser beams impinging on photocathodes, and the positron bunches by improved versions of the positron source now used on the SLC. After initial acceleration to about 2 GeV by various L-band and S-band preaccelerators, these bunches will be compressed by a factor of 100 in height and 10 times in width by circulating them for several milliseconds in damping rings. A full-scale prototype of such a damping ring is now being tested at KEK's Accelerator Test Facility (see photos on pages 16, 18, and opposite) where scientists from Japan, Europe, and the United States are performing joint experiments and making good progress.

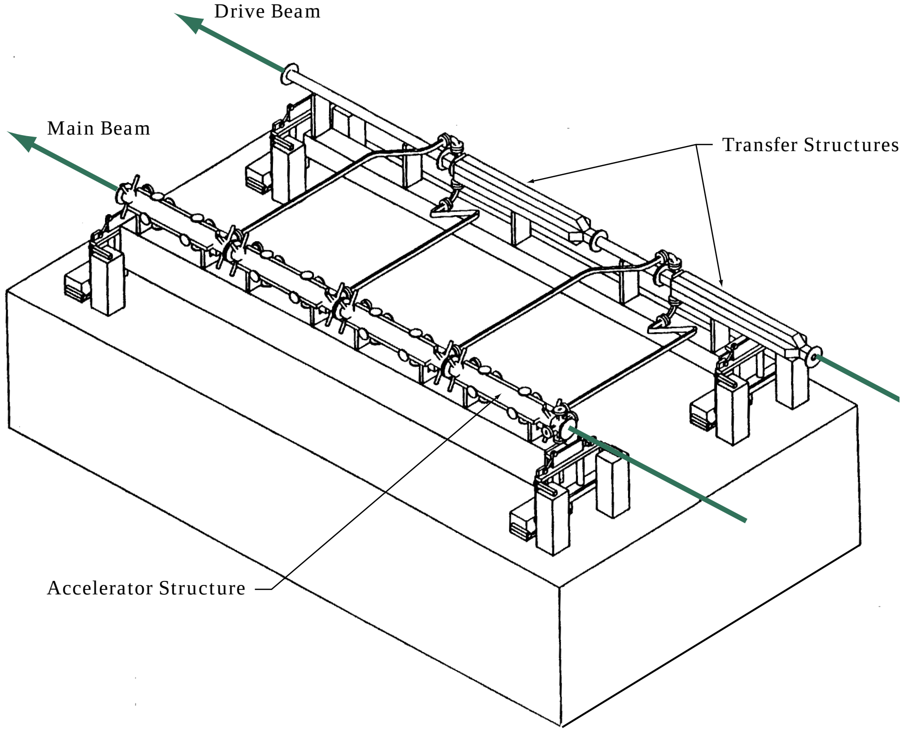
Seven Russian institutions have been collaborating on the VLEPP design with physicists from Finland to Japan. This machine would accelerate only a single bunch of electrons or positrons in each microwave pulse, thus eliminating the wakefield problems of the multibunch designs. But VLEPP must achieve its high luminosity by cramming about twenty times more particles into each bunch, which leads to higher backgrounds when the bunches collide at the interaction point. Although the VLEPP project is on hold because of lack of funding, BINP scientists continue to make important contributions by performing specialized microwave and other studies at home and abroad.



Juwen Wang, Ted Lavine, and Chris Adolphsen with the Next Linear Collider Test Accelerator.

The JLC, NLC, and VLEPP linacs can be upgraded in energy by increasing their active length and/or adding microwave power. Another approach to boosting the NLC energy is being explored by groups at the Lawrence Berkeley and Livermore National Laboratories; this involves the use of a parallel 10 MeV "drive beam" accelerated in an induction linac to generate the microwave power. If successful, such a two-beam technology may replace klystrons in the next decade or two.

The CERN, or Compact, Linear Collider (CLIC) involves a dozen institutions, mainly from Europe but also including the U.S. and Japan, that are combining their R&D efforts on another two-beam accelerating technology that has been pioneered by CERN. This unique machine would operate at the highest microwave frequency, 30 GHz, and have potentially the highest accelerating gradient. But it also has the strongest wakefields, and therefore the tightest fabrication and alignment tolerances, and it requires a number of innovations. Accelerated by LEP-style superconducting cavities, a very intense 3 GeV



A section of the proposed CLIC two-beam accelerator. An intense, low-energy drive beam generates microwave pulses that accelerate electrons or positrons in the main linac.

drive beam induces microwave pulses in transfer structures that transmit these pulses over to the main linac (see illustration above), where they boost bunches of electrons or positrons to their ultimate energies. The challenge of manufacturing thousands of klystrons, modulators and microwave pulse compressors is replaced by the need to develop two high-current beams that can generate high-frequency pulses of the required square-wave shape.

One advantage of the CLIC scheme is that most of the components can be housed in a single tunnel, thus lowering conventional construction costs. But certain features of the drive and main beams remain to be determined—particularly for operation at 60 particle bunches per microwave pulse, which is needed to raise the luminosity to the level of the other designs. These questions will be examined in experiments on the CLIC Test Facility, a 30 m long accelerator that began operation at CERN in 1995 and is now undergoing a major upgrade.

HAVING READ thus far, you may well wonder whether this entire effort is a collaboration, or an intense global competition. Such a reaction would not be totally unwarranted. Although they all share similar problems, TESLA, the "conventional" microwave machines, and CLIC are very different designs. As it seems unlikely, and is probably undesirable, for the world to build more than one TeV linear collider, you may well ask, "How will the present situation unfold?"

In attempting to answer this question, we can only speculate. The linear-collider community has recently bifurcated into two distinct coalitions. KEK, SLAC, and other institutions interested in X-band colliders are gradually joining forces to work toward a single design. DESY and its collaborators are focusing on the superconducting TESLA approach, with SBLC as a backup. These two coalitions intend to prepare conceptual design reports—including complete engineering studies and cost estimates—by the turn of the century. The CLIC program will continue doing R&D until 1999 and then undergo a broad review to determine how to proceed. Since this two-beam technology offers potential accelerating gradients above 100 MV/m, a design based on it may eventually lead to a third-generation linear collider operating at 1–3 TeV.

From all these efforts, it should be possible to draw some useful and fairly definitive comparisons. Whatever is learned, we hope that countries interested in working on a linear electron-positron collider will eventually join forces and jump on the best bandwagon. In the past, however, a serious obstacle to building an accelerator or collider internationally was the difficulty of agreeing on a single site.

This difficulty is not scientific, nor is it rooted in nationalism—or at least it shouldn't be. Physicists have stood at the forefront of the global movement toward internationalism; they have extensive experience working together on common projects. The difficulty is mainly cultural: where to live, what food to eat, what coffee shop to frequent, what language to speak at the supermarket, where the children go to school. CERN solved this knotty problem many years ago, but in the midst of a relatively homogeneous European culture. The next—and truly international—leap will be substantially greater. Perhaps the resolution lies in the extensive use of jet planes and high-speed computer networks. To some extent, it should be possible for many—but not all—collaborators to remain situated around the globe and still make important contributions to an international linear collider.