The Next Linear Collider†

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Abstract

The ability to study nature with both electron-positron and hadron-hadron collisions has proven essential to the advancement of our understanding of particle physics. This will remain true as we seek answers to questions posed at the TeV energy scale. The LHC in Europe offers an entry into the TeV energy regime with significant opportunity for discovery. The companion electron-positron collider at this next step in energy will make possible complementary experimental investigations with unique capabilities for discovery and precision measurement. International research and development of the accelerator physics and technologies required to design and build a TeV-scale linear collider have come to fruition in the past several years, and the feasibility of such a collider has now been firmly established.

† Also as, "Physics and Technology of the Next Linear Collider: A Report Submitted to Snowmass '96" [NLC 1996].

I. Goals for the Next Linear Collider

For the past 25 years accelerator facilities with colliding beams have been the forefront instruments used to study elementary particle physics at high energies (Figure 1). Both hadron-hadron and electron-positron colliders have been used to make important observations and discoveries. Direct observations of the $W^{\pm}$ and Z^0 bosons at CERN and investigations of the top quark at Fermilab are examples of physics done at hadron colliders. Electron-positron colliders provide well-controlled and well-understood experimental environments in which new phenomena stand out and precise measurements can be made. The discoveries of the charm quark and τ lepton at SPEAR, discovery of the gluon and establishment of QCD at PETRA and PEP, and precision exploration of electroweak phenomena at the SLC and LEP are highlights of the results produced by experiments at electron-positron colliders.

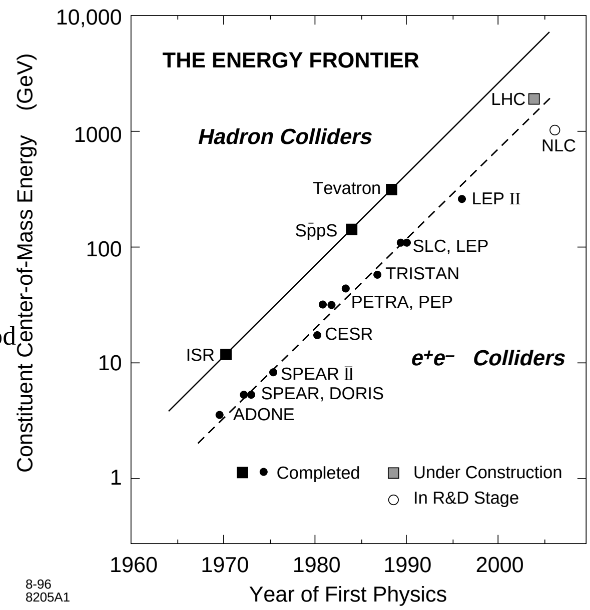

Figure 1. The energy frontier of particle physics. The effective constituent energy of existing and planned colliders and the year of first physics results from each.

The ability to study nature with these two different kinds of instruments has proven essential to the advancement of our understanding of particle physics. This will remain true as we seek answers to questions posed at the TeV energy scale:

- What is the top quark, and what are its interactions?
- Why is the symmetry of the electroweak interaction broken, and what is the origin of mass?
- Do Higgs particles exist? If so, how many, and what are their structures and interactions?
- Is the world supersymmetric, and if so, what is its structure, and is this supersymmetry part of a larger unification of nature?
- Are quarks, leptons, and gauge bosons fundamental particles, or are they more complex?
- Are there other new particles or interactions, and what might nature contain that we have not yet imagined?

The Large Hadron Collider (LHC) in Europe offers an entry into the TeV energy regime with significant opportunity for discovery of new phenomena. The planned participation in the design, construction, and utilization of this collider by nations around the world will make the LHC the first truly global facility for the study of particle physics.

The companion electron-positron collider at this next step in energy, the Next Linear Collider (NLC), will provide a complementary program of experiments with unique opportunities for both discovery and precision measurement. To understand the nature of physics at the TeV scale, to see how the new phenomena we expect to find there fit together with the known particles and interactions into a grander picture, both the LHC and the NLC will be required.

Studies of physics goals and requirements for the next-generation electron-positron collider began during the late 1980's in the United States [Ahn 1988, Snowmass 1988, Snowmass 1990], Europe [LaThuile 1987, DESY 1990], and Japan [JLC 1989, JLC 1990]. These regional studies evolved into a series of internationally sponsored and organized workshops [Saariselka 1991, Hawaii 1993, Morioka 1995] that have allowed global participation in the evaluation of the physics capabilities and specifications of future e^+e^- colliders.

Study in the United States of the physics opportunities offered by a TeV-scale linear collider became more vigorous following cancellation of the SSC. To prepare for Snowmass, national working groups were established to provide a framework for people to participate in discussions of various topics in physics and experimentation at linear colliders. Nearly 500 U.S. physicists were able to participate in one or more of the workshops organized by these groups at Fermilab, SLAC, and Brookhaven over the past year.

Unlike a storage ring, a linear collider can operate over a broad range of center of mass energies, and a picture has emerged of a high-performance collider that allows exploration of physics from a few hundred GeV to a TeV and, with appropriate improvements, to energies beyond (Figure 2). The capability to control the beam energy and the availability of polarized beams are very powerful tools that can be used to isolate differing particle states and their interactions. The colliding electron and positron beams produce a predominance of electro-weak final states unencumbered by large backgrounds from strongly interacting particles, and electron-positron annihilation converts the entire beam energy into the final state, so it is possible to build detectors able to fully reconstruct the fine details of each event. Especially powerful is the ability to constrain in vertex detectors the origin of each event to the small sub-micron region of beam interactions. These features make possible unique experimental searches for new phenomena and precision measurements that will be essential to our understanding of particle physics at the TeV energy scale.

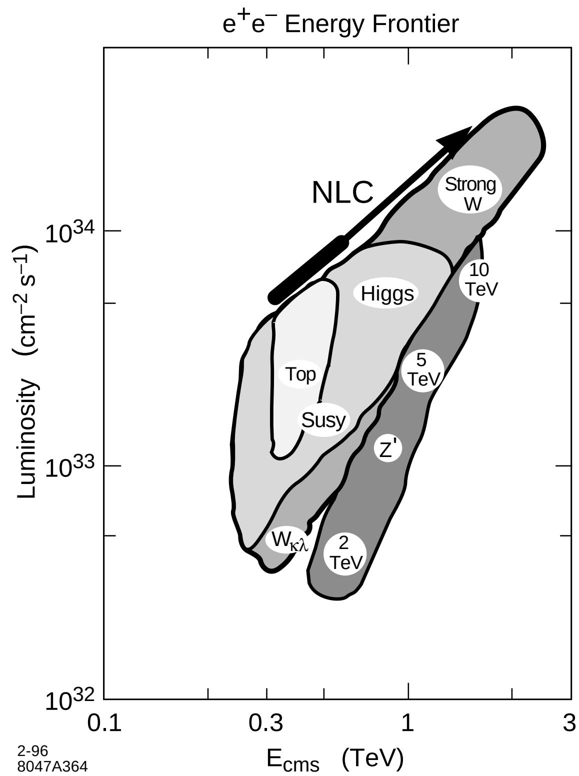

Figure 2. Physics goals for a TeV-scale e^+e^- collider.

II. Accelerator Design Choices

A. The Stanford Linear Collider

The Stanford Linear Collider (Figure 3) was conceived and built to accomplish two goals: to study particle physics at the 100-GeV energy scale, and to develop the accelerator physics and technology necessary for the realization of future high-energy colliders. The SLC was completed in 1987 and provided a first look at the physics of the Z^0 in 1989. In time, the luminosity provided by this machine has grown steadily (Figure 4), and has allowed particle physicists to make unique and important studies of the Z^0 and its decays.

The design of the Next Linear Collider (NLC) is intimately connected with experiences gained at the SLC, and our choices of technologies and philosophies of design have direct links to these experiences and considerable overlap with them. Lessons have been learned and

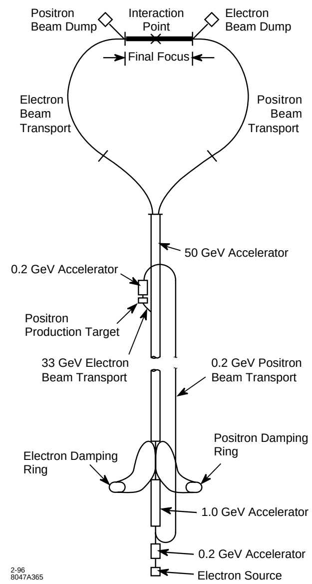

Figure 3. The Stanford Linear Collider (SLC).

techniques developed at the SLC that are relevant to the design and implementation of every part and system of the NLC:

- Injectors
  – Stabilized high-power electron sources
  – Polarized electrons
  – High-power targets and positron capture

- Damping Rings
  – Stabilized fast (50 ns) injection and extraction systems
  – Sub-picosecond phase synchronization with linac rf systems

- Linear Accelerator
  – Beam Acceleration
    Management of large rf systems
    Rf phase control
    "Time-slot" compensation
    Short-range longitudinal wake compensation
    Multibunch beam loading compensation
  – Emittance Preservation
    Beam-based alignment
    LEM—lattice/energy matching
    BNS damping
    Coherent wakefield cancellation
    Dispersion-free steering

- Final Focus Systems
  – Second-order chromatic optics and tuning
  – Precision diagnostics
  – Beam-beam control and tuning

- Experimentation
  – Theory and modeling of backgrounds
  – Vulnerability of detector technologies
  – Collimation—theory and implementation

- Systems Performance and Operation
  – Precision instrumentation—BPMs and wirescanners
  – Feedback theory and implementation
  – Importance of on-line modeling and analysis
  – Automated diagnostics and tuning
  – Mechanical stabilization of supports and components
  – Thermal stabilization of supports and components
  – Reliability
  – History monitoring (from seconds to years)

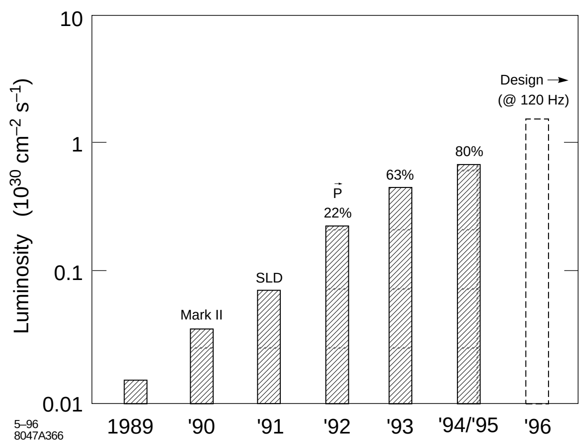

Figure 4. Performance of the SLC from early commissioning. Polarization of the electron beam is also shown.

B. Future Linear Colliders

The basic components of any linear collider are those already incorporated into the SLC (Figure 5). The energy of such a future collider must be ten times that of the SLC, and a TeV-scale collider must be able to deliver luminosities that are several orders of magnitude greater than those achieved at the SLC. Trains of bunches of electrons and positrons are created, condensed in damping rings, accelerated to high energy, focused to small spots, and collided to produce a luminosity given by

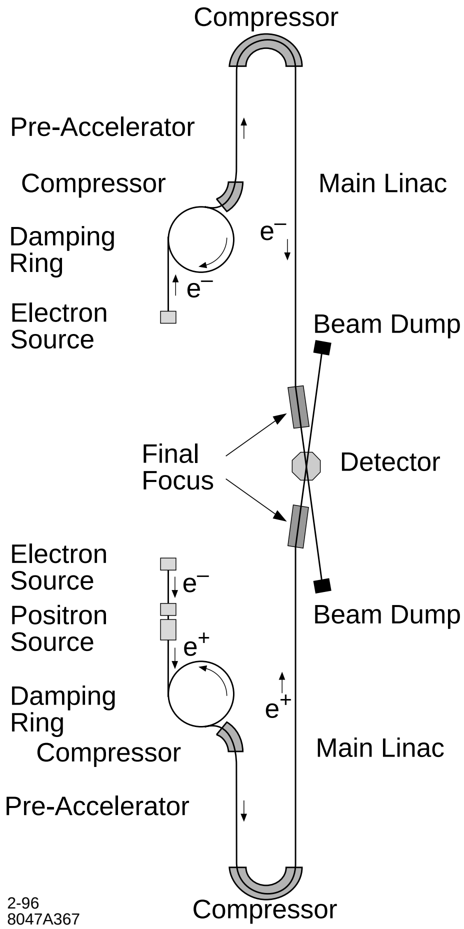

Figure 5. Schematic of a TeV-scale linear collider.

$$L = \frac{nN^2Hf}{4\pi\sigma_x^*\sigma_y^*} \quad ,$$

where

n = number of bunches per train,

N = number of particles per bunch,

H = beam pinch enhancement,

f = machine repetition rate,

and σ_x^* and σ_y^* are the horizontal and vertical beam dimensions at the collision point. The luminosity can be written as

$$L = \frac{1}{4\pi E}\,\frac{NH}{\sigma_x^*}\,\frac{P}{\sigma_y^*} \quad ,$$

where P is the average power in each beam. The factor N/σ_x^* determines the number of beamstrahlung photons emitted during the beam-beam interaction, and since these photons will alter the effective spread in beam collision energies and can create backgrounds in experimental detectors, this factor is highly constrained. It is mainly the last ratio, P/σ_y^*, that can be addressed by accelerator technology; high luminosity corresponds to high beam power and/or small beam spots. These two parameters pose different, and in many cases contrary, challenges to the accelerator physicist, and several technologies that represent differing degrees of compromise between beam power and spot size are being developed. Table I summarizes the initial stage of the mainstream design choices.

Each of the technologies in Table I is being pursued at laboratories around the globe. This strong international effort is remarkably well coordinated through collaborations that together provide a set of test facilities to address each of the important aspects of the collider design and implementation. A summary of the facilities presently in operation or under construction is given in Table II.

III. The Next Linear Collider

A. Technology Choice and Design Philosophy

The goal to reach 1 to 1.5-TeV cms energy with luminosities of 10^{34} cm^{-2} s^{-1} or more, and our experiences with the SLC, guide our choice of technologies for the NLC. We believe that the most natural match to these design goals is made with normal-conducting X-band (11.424 GHz) microwave components patterned after the S-band technology used in the SLC. A schematic of a section of the rf system of the NLC is shown in Figure 6. Our choice of technology has required the development of new advanced rf klystrons and pulse-compression systems, but provides confidence that accelerating gradients of 50–100 MV/m can be achieved and used in the implementation of the collider. The technical risk of building a collider with new X-band technologies is perhaps greater than simply building a larger SLC at S-Band, but the goal to reach 1–1.5 TeV is substantially more assured, and capital costs to reach these energies will be lower.

The NLC is designed with nominal cms energy of 1 TeV. It is envisaged to be built with an initial rf system able to drive the beams to 0.5-TeV cms energy, but with all infrastructure and beam lines able to support 1 TeV. The rf system design incorporates the ability to replace and add modulators and klystrons without access to the accelerator beam line (dashed lines in Figure 6), so an unobtrusive, smooth, and adiabatic transition from 0.5 TeV to 1 TeV cms energy can be made with modest and ex-

Table I. Linear collider design parameters (E_{cms} = 500 GeV).

	Frequency (GHz)	Gradient (MV/m)	Total Length (km)	Beam Power (MW)	σ_y (nm)	Luminosity (10^{33} cm^{-2} s^{-1})
SuperC	1.3	25	30	8.2	19	6
S-Band	3.0	21	30	7.3	15	5
X-Band	11.4	50	16	4.8	5.5	6
2-Beam	30.0	80	9	2.7	7.5	5

Table II. Linear collider test facilities around the world.

Facility	Location	Goal	Operations
SLC	SLAC	Prototype Collider	1988
ATF	KEK	Injector and Damping Ring	1995
TTF	DESY	SuperC Linac	1997
SBTF	DESY	S-band Linac	1996
NLCTA	SLAC	X-band Linac	1996
CTF	CERN	2-Beam Linac	1996
FFTB	SLAC	Final Focus/IR	1994

pected improvements in X-band technology. This allows the collider to begin operation with the greatest of margins in cost and performance, and provides an excellent match to the anticipated physics goals at the energy frontier (Figure 2). Our philosophy is akin to that taken previously in the construction of the SLAC linac which provided a 17-GeV electron beam at its inauguration, was improved to 35 GeV, and with continued advances in S-band technology, now provides 50-GeV electrons and positrons for the SLC.

The NLC design also incorporates multiple paths to further upgrade the cms energy to 1.5 TeV. The "trombone" shape of the collider layout would easily accommodate a straightforward albeit expensive increase in the length of the main accelerators without requiring extensive modification of the remainder of the complex. This final energy might also be accomplished by development of new, more efficient, X-band technologies; for example, gridded klystrons, cluster klystrons, or relativistic two-beam klystrons.

The highest-level parameters of the NLC are listed in Table III. At each of the nominal 0.5- and 1-TeV cms energies, three sets of parameters define the operating plane of the collider. The expected luminosity is constant over the operating plane, but is achieved with differing combinations of beam current and spot size. This provides a *region* in parameter space where the collider can be operated. Construction and operational tolerances for the various subsystems of the collider are set by the most difficult portion of the operating region. For example, the more difficult parameters for the final focus are those of case (a) in Table III, for which the beam height is smallest. In contrast, preserving the emittance of the beam in the linac is more difficult in case (c), in which the beam charge is highest and the bunch length longest. This design philosophy builds significant margin into the underlying parameters of the collider.

An important element in the design strategy of the NLC is the use of the beam to measure and correct or compensate for errors in electrical and mechanical parameters of the accelerator. These techniques, many in extensive use at the SLC and FFTB, are able to achieve far greater accuracy than is possible during fabrication and installation of components. For example, the use of optical matching and beam-based alignment algorithms considerably loosen tolerances required on magnet strengths and positioning. These procedures require accurate measurement of the properties of the beam and extensive online modeling and control software. The existence of instrumentation suitable for these purposes is an important

Table III. High-level parameters and operating region in parameter space of the NLC.

	NLC-Ia	NLC-Ib	NLC-Ic	NLC-IIa	NLC-IIb	NLC-IIc
Nominal CMS Energy (TeV)		0.5			1.0	
Repition Rate (Hz)		180			120	
Bunches Pulse		90			90	
Bunch Separation (ns)		1.4			1.4	
Bunch Charge (10^{10})	0.65	0.75	0.85	0.95	1.10	1.25
Beam Power (MW)	4.2	4.8	5.5	6.8	7.9	9.0
σ_x at IP (nm)	264	294	294	231	250	284
σ_y at IP (nm)	5.1	6.3	7.8	4.4	5.1	6.5
σ_z at IP (μm)	100	125	150	125	150	150
Pinch Enhancement H	1.4	1.4	1.5	1.4	1.4	1.5
Beamstrahlung δ_E (%)	3.5	3.2	3.5	12.6	12.6	12.1
No. Photons per e^-/e^+	0.97	1.02	1.16	1.65	1.77	1.74
Max. Beam Energy (GeV)	267	250	232	529	500	468
Luminosity (10^{33})	5.8	5.5	6.0	10.2	11.0	10.6
No. Klystrons		4528			9816	
Klystron Peak Power (MW)		50			75	
Pulse Compression Gain		3.6			3.6	
Unloaded Gradient (MV/m)		50			85	
Total Linac Length (km)		17.6			19.1	
Beam Delivery Length (km)		10.4			10.4	
Total Site Length (km)		30.5			30.5	
Total Linac AC Power (MW)		120			193	

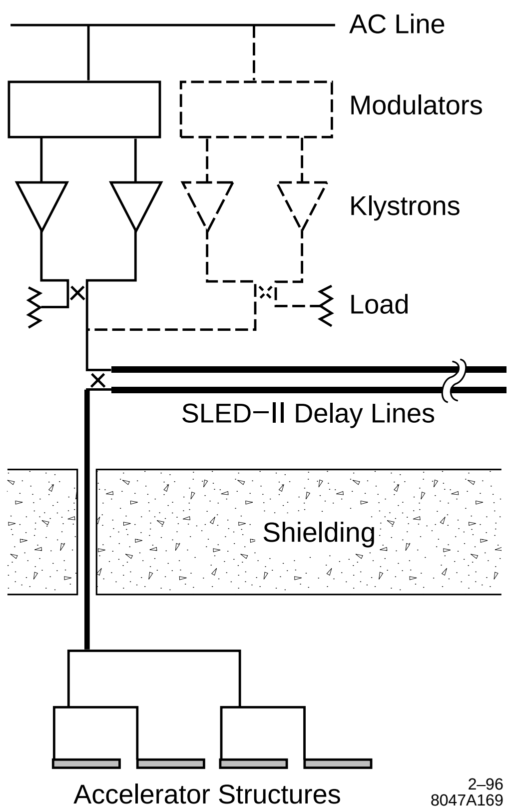

Figure 6. Normal-conducting rf system module in NLC main linacs. The dashed elements are expected to be necessary to reach 1 TeV cms energy.

aspect of the readiness of technologies for the collider.

Additional performance overhead has been included in the designs of most subsystems of the NLC. Errors that we anticipate will occur during machine tuning operations have been taken into account. For example, the injector systems are designed to provide 20% more charge than is indicated in Table III. Fabrication and alignment tolerances for main linac structures are specified without assuming benefit from certain global tuning methods such as coherent wakefield cancellation. These are powerful techniques in routine practice at the SLC, but our philosophy is to use them only to provide operational margin. We also recognize that the beam-based tuning described above cannot be done with perfect accuracy. For example, we have analyzed the tuning procedure for the final focus and estimated a 30% increase in the spot size at the IP due to errors that we anticipate will occur in measuring and correcting aberrations inherent in the optics. (This is included in Table III.) This layered approach to specification of collider performance is an important part of our design philosophy.

B. Status Report on Technlologies for the NLC

Progress in development of X-band rf components has been impressive in recent years. Prototype klystrons now produce 50-MW pulses, over 1.5 microseconds long, with performance characteristics that are correctly modeled by computer codes. The most recent prototype produces microsecond-long 75-MW pulses. This exceeds the requirements of the initial 0.5-TeV stage of the NLC, and indeed approaches the requirements for 1-TeV cms energy. Tests of rf pulse-compression transformers have exceeded most goals of the NLC, and high-power rf windows and mode converters that allow high-efficiency transfer of power between components have been successfully tested. Examples of some of these results are shown in Figure 7.

The voltage gradient that can be used in a particle accelerator can be limited by the dark current created when electrons are drawn from the surfaces of the accelerator structures and captured on the accelerating rf wave. For a given rf frequency, there is a well-defined gradient beyond which some electrons emitted at rest will be captured and accelerated to relativistic velocities. This threshold gradient is about 16 MV/m at S-band, and scales to 64 MV/m at X-band. These are not actual limits to gradients that can be utilized in an accelerator since much of the charge is swept aside by the focusing quadrupoles of the machine lattice, but the dark current will grow rapidly above these values, and may adversely affect the primary beam or interfere with instrumentation needed for tuning. Gradients somewhat above the capture threshold are likely to be useful in practice, but the operational limits are not well known since no large-scale high-performance facility has been operated significantly above capture threshold. Expected thresholds of dark currents in S-band and X-band structures have been confirmed, and it has been proven that (unloaded) gradients as large as 70 MV/m can be used at X-band (Figure 8).

The electro-mechanical design of the structures of the main accelerator must not only produce the desired gradient, but must also minimize wakefields excited by the passage of the beam. The retarded electromagnetic fields left by each particle can disrupt the trajectories of particles that follow it through the accelerator. Many techniques to control the effects of the short-distance, intrabunch wakefields have been developed, tested, and put into use at the SLC. It will be necessary to also control long-range wakefields at the NLC in order to allow trains of closely spaced bunches to be accelerated on each rf pulse.

Structures in which wakefields are suppressed by careful tuning of their response to the passage of the beam

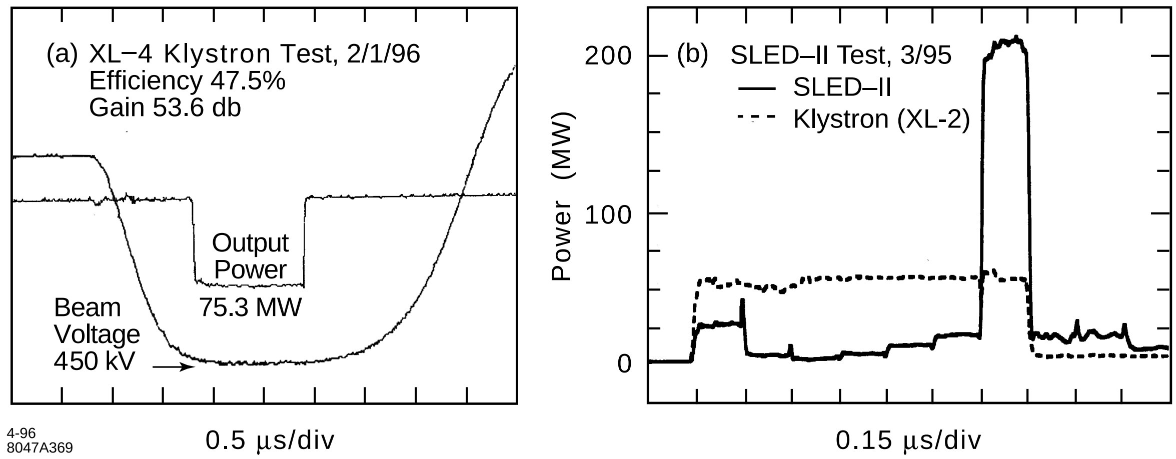

Figure 7. Results of tests of X-band rf components: (a) high-power klystrons, and (b) pulse compression systems.

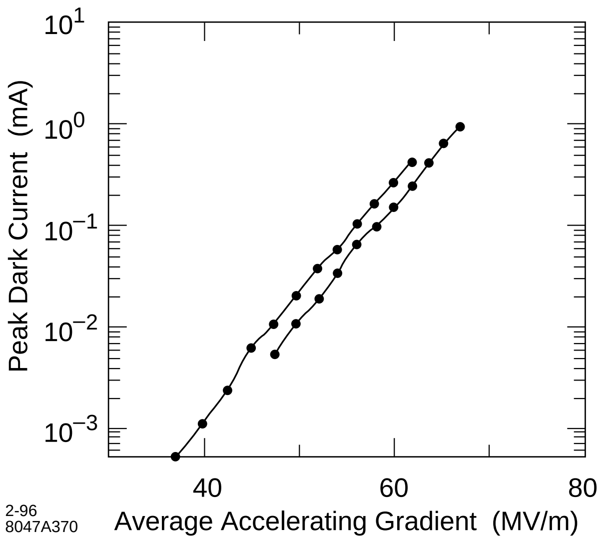

Figure 8. Processing of X-band accelerator structures to high gradient.

have been developed, and tests have been performed at a facility (ASSET) installed in the SLAC linac (Figure 9). Agreement with theoretical expectations is excellent and lends confidence to the design and manufacture of these structures. A more advanced design that further mitigates the long-range wakefields by coupling deflecting rf modes to external energy-absorbing materials has been completed, and a prototype of this new structure has been successfully tested in ASSET as well.

Work remains to be done on X-band rf technologies, but with prototype components now in hand, tests of completely integrated systems have begun. A fully engineered test accelerator is under construction at SLAC that will allow optimization of rf systems and provide experience with beam operations at X-band frequencies. This test accelerator will be a 40-m long beam line containing six 1.8-m-long X-band structures powered by 50–75 MW klystrons to an accelerating gradient of 50–85 MV/m. Commissioning of this facility has begun, and operations are expected to be underway by the end of this year (Table II).

The spot sizes that must be produced at the interaction point of the NLC represent significant extrapolations from those achieved at the SLC. It is important to demonstrate that it is possible to demagnify a beam by the large factor needed in the NLC. An experiment has been performed by the Final Focus Test Beam (FFTB) Collaboration to show that such large demagnifications can be achieved. The FFTB is a prototype beam line installed in a channel located at the end of the SLAC linac at zero degrees extraction angle. The FFTB lattice is designed to produce a focal point at which the beam height can be demagnified by a factor of 380 to reduce the SLC beam ($\gamma\varepsilon_y = 2 \times 10^{-6}$ m-rad) to a size smaller than 100 nm. The demagnification factor of the FFTB beam line is well in excess of that needed for the NLC.

The FFTB optics are chromatically corrected to third order in the beam energy spread. (The SLC is corrected to second order.) All magnetic elements are mounted on precision stages that can be remotely positioned with step size of about 0.3 micron, and beam-based alignment procedures were developed that successfully place these elements to within 5–15 microns of an ideal smooth trajectory. New state-of-the-art instruments were developed and used to measure the FFTB beam positions and spot sizes.

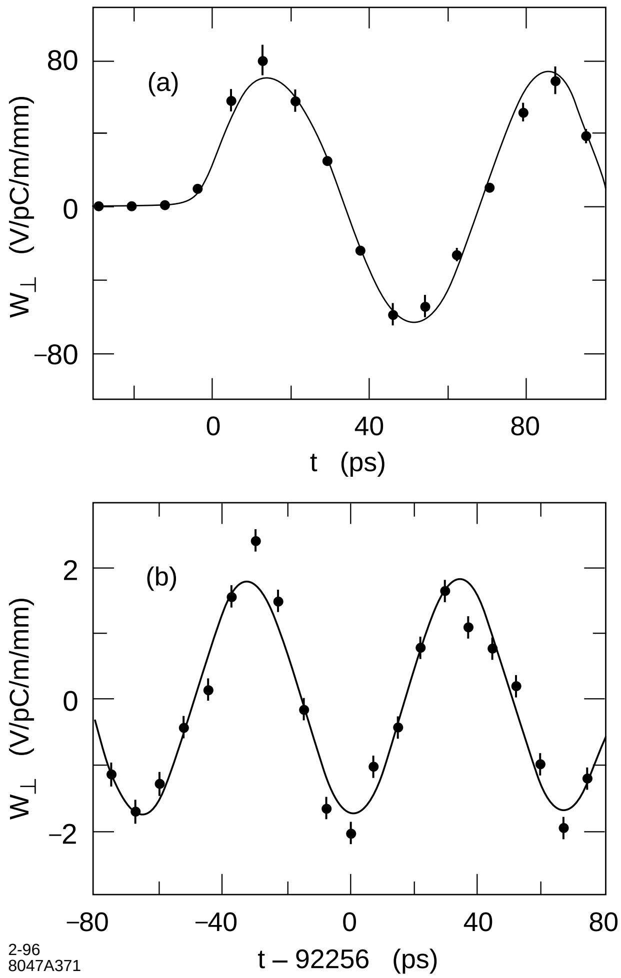

Figure 9. Measured and predicted transverse dipole wakefields in a 1.8-m-long X-band accelerator structure.

Following a brief shake-down run in August of 1993, data were taken with the FFTB during a three-week period in April and May of 1994. Beam demagnifications of 320 and spot sizes of 70 nm were controllably produced during this period. Measurements of these beams are shown in Figure 10. The design of the NLC final focus follows that of the FFTB, and the experiences gained from the FFTB are incorporated into the tuning strategies for the NLC.

Important advances have also been made in instrumentation required to measure and control properties of the beams. The SLC control system has evolved dramatically over the past years to include extensive online modeling and automation of data analysis and tuning procedures. Scheduled procedures use sets of wire scanners to make complete measurements of the beam phase space,

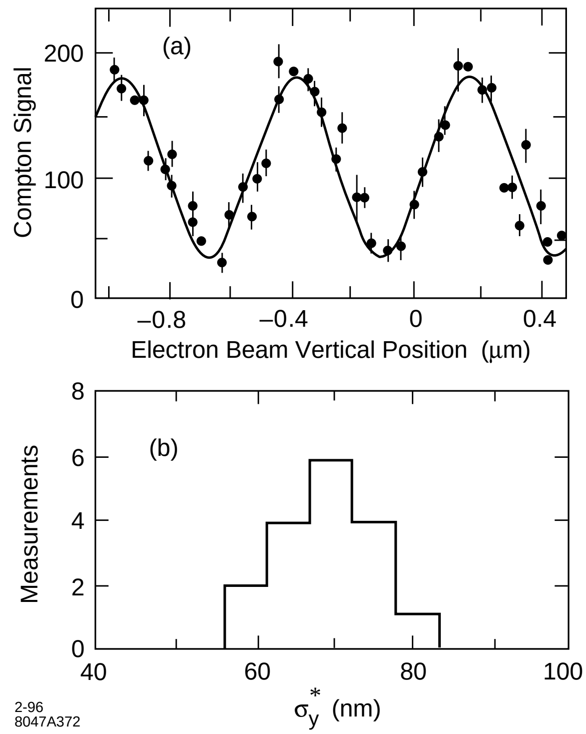

Figure 10. Measurement of 70-nm beam spots with a laser-Compton beam size monitor in the FFTB. (a) The rate of Compton scatters from a laser interference pattern used to determine the beam size, in this case 73 nm. (b) Repeatability of spot measurement over periods of several hours.

and provide recorded histories of machine performance. Online data-analysis packages are able to reconstruct fully coupled non-linear optical systems. Beam-based feedback and feedforward loops are in routine operation in the SLC with over 100 loops providing control of beam trajectories and energies. Beam position monitors have been developed for the FFTB that achieve pulse-to-pulse resolutions of 1 micron, and new position monitors have recently been installed that are able to measure beam motions of 100 nm. The FFTB focal-point spot monitors have demonstrated techniques to measure beam sizes of 30–40 nm, and extrapolation of these techniques to sizes as small as 10 nm is expected to be successful.

IV. Outlook for the Next Linear Collider

As the SLC has systematically increased its luminosity, the accelerator physics and technologies of linear colliders have matured. Experiences and lessons learned from the task of making this first collider perform as an instrument for studies of particle physics are a strong foundation on which to base the design and technology choices for the next linear collider. At the same time, essential demonstrations of new collider technologies have either taken place or soon will be underway. The experimental program with the FFTB is providing the experience needed to evaluate limitations to designs of final focus and interaction regions. The ability to demagnify beams by the amount required for the NLC has already been achieved. Microwave power sources have exceeded requirements for the initial stage of the NLC, and critical tests assure us that this technology can be expected to drive beams to center-of-mass energies of a TeV or more. Fully integrated test accelerators are presently under construction at CERN, DESY, KEK, and SLAC that will soon provide answers to questions of technical optimization and costs of the major components of a TeV-scale collider.

Given the great international interest and commitment to the goals of a TeV-scale high-performance e^+e^- collider, it is certain that the final design, construction, and utilization of such a collider will be a global effort. It is important that the scientific community put into place foundations for such a collaboration. The international character of the linear collider project is already reflected in the collaborations at work on the accelerator physics and technology of linear colliders, and in the process of international discussion and review of progress in the field [TRC 1995]. It is essential that we continue to build on this base of understanding and cooperation, and make certain that all involved in this enterprise are full parties in its final realization.

References

[LaThuile 1987] Proceedings of the 1987 LaThuile Meeting: Results and Perspectives in Particle Physics, M. Greco, ed., Gif-sur-Yvette, France, 1987.

[Ahn 1988] C. Ahn, *et al.* SLAC-report-329, 1988.

[Snowmass 1988] Proceedings of the 1988 DPF Summer Study: Snowmass '88, High Energy Physics in the 1990s, F. Gilman, ed., Snowmass, Colorado, 1988.

[JLC 1989] Proceedings of the First Workshop on Japan Linear Collider (JLC I), S. Kawabata, ed., KEK, 1989.

[Snowmass 1990] Proceedings of the 1990 DPF Summer Study on High Energy Physics: Research Directions for the Decade, E.F. Berger, ed., Snowmass, Colorado, 1990.

[DESY 1990] Workshop on Electron-Positron Collisions at 500 GeV: The Physics Potential, DESY, 1990.

[JLC 1990] Proceedings of the Second Workshop on Japan Linear Collider (JLC II), KEK, 1990.

[Saariselka 1991] Proceedings of the First International Workshop on Physics and Experiments with Linear Colliders, R. Orava, ed., Saariselka, Finland, 1991.

[Hawaii 1993] Proceedings of the Second International Workshop on Physics and Experiments with Linear Colliders, F. Harris, *et al.*, eds., Waikoloa, Hawaii, 1993.

[Morioka 1995] Proceedings of the Third International Workshop on Physics and Experiments with Linear Colliders, S.Iwata, ed., Iwate, Japan, 1995.

[TRC 1995] International Linear Collider Technical Review Committee Report 1995, G. Loew, ed., available from the editor.

[NLC 1996] Physics and Technology of the Next Linear Collider: A Report Submitted to Snowmass '96, S. Kuhlman, *et al.*, available as BNL 52-502, Fermilab-PUB-96/112, or SLAC Report 485.