SLC Status and NLC Design and R&D*

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Introduction

In this paper, we will first review the status of the Stanford Linear Collider (SLC). In particular, we will discuss the luminosity and performance issues and the accelerator studies that relate to future linear colliders. Next, we will describe the present state of the Next Linear Collider (NLC) design and the ongoing R&D effort which is, in addition to the work at the SLC, supporting the design. This includes extensive ground motion measurements to verify the required stability, measurements of the dipole wakefields to verify the performance of the Damped-Detuned accelerator Structures (DDS), and tests of the rf structure BPMs that are needed to align the structures to the beam trajectory. It also includes the development and fabrication of the X-band structures, klystrons, and rf pulse compressors that are needed to accelerate the beams with gradients in excess of 50 MV/m.

It should be noted that much of the material reported here is described in greater detail in other papers submitted to this conference and thus the appropriate references are included throughout. In addition, because of space limitations, we only briefly describe the design of the NLC and, instead, concentrate on the R&D that is supporting the design; detailed descriptions of the NLC design can be found in Refs. [1, 2, 3].

SLC Status

The 1996 SLC/SLD physics run was not as successful in terms of luminosity as was initially expected. There were numerous operational difficulties, including a fire in the cable tray of the North Damping Ring, a dirty vacuum vent in the same ring, and poor accelerator availability. The poor availability and frequent faults made optimizing the luminosity difficult. Regardless, the average luminosity during the physics run was slightly better than that obtained during the 1994–1995 collider run; the luminosity recorded by the SLD detector per week and the integrated luminosity are plotted in Fig. 1. The increase in average luminosity was primarily due to an increase in the beam currents at the IP. The charge per bunch was increased from $N \approx 3.5 \times 10^{10}$ in 1994 and 1995 to roughly $N \approx 4 \times 10^{10}$ in 1996.

Although the 1996 collider run did not attain the luminosity desired, a new high resolution vertex chamber, the VXD3, was commissioned in the SLD and an enormous amount was learned about both the operation of the SLC as well as the accelerator physics and operational issues relevant to a future linear collider. In particular, significant progress was made in the following areas:

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- Beam-based feedbacks
- Beam collimation and collimator wakefields
- Beam jitter
- Sub-micron beam size diagnostics.

We will describe each of these issues in more detail subsequently.

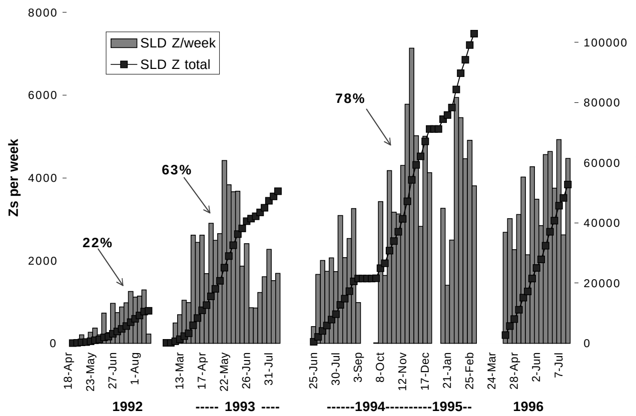

Figure 1: Luminosity history in the SLC.

Beam-Based Feedbacks

The SLC utilizes over 30 fast beam-based feedback loops to control and stabilize the beams and most future linear collider designs are even more heavily reliant on the beam-based feedback systems. Unfortunately, during the previous SLC runs, it was found that the gain, and thereby the frequency response, of the feedback systems had to be reduced substantially to prevent the feedbacks from oscillating [4]. This was found to be especially true in the linac where many feedbacks are 'cascaded' to prevent them from interfering with each other. The principle of the cascade is that each feedback loop transmits what it measures to the next downstream loop with the assumption that the trajectory deviation will be corrected and thus the downstream feedback should not respond to it. To allow the cascade system to adapt to changes in the optics and the energy profile along the linac, the cascade transfer matrices are calculated adaptively from the natural beam jitter.

Studies during the 1994–95 and 1996 collider runs, identified three primary performance limitations:

- Feedback transfer matrices had significant errors — partly due to optics modification from transverse wakefields,
- Cascade assumes purely linear transport matrices through the linac and thus the feedback loops only talk to the next downstream loop but wakefields and chromatic effects make the linac transport nonlinear,
- Cascade adaption does not correctly account for the finite BPM resolution yielding incorrect transfer matrices between feedback loops.

After these problems were identified, near perfect performance was attained at low currents, where the wakefields are less important, and when the cascade matrices were calculated from dedicated oscillations where the measurements were not limited by the finite BPM resolution. This was important because it verified the feedback principles although it suggested that the algorithms need to be modified. In the future, at the NLC, the cascade matrices will likely be calculated from dedicated oscillations and the cascade system will be modified to account for the nonlinearity of the beam transport through the linac.

During the diagnostic process another important realization was made, namely, that different feedback algorithms have dramatically different sensitivities to errors. The SLC beam-based feedbacks do not use very aggressive algorithms. The cross-over frequency, below which the feedback damps rather than amplifies incoming oscillations, is $\frac{1}{30}f_{rep}$, where f_{rep} is the sample rate. In the past, members of the linear collider community have suggested using far more aggressive feedback systems. For example, the simple double-dead-beat system, which uses the two previous measurements to estimate the next, has a higher crossover frequency, $\frac{1}{6}f_{rep}$, and a faster rate of damping. Unfortunately, these systems were found to be extremely sensitive to errors. In fact, even relatively small changes to the SLC feedback algorithms were seen to perform much worse when realistic errors were included. At this time, the details of the error sensitivity are not understood and this requires additional study.

Beam Collimation

During the 1994–1995 SLC run, it was noticed that optimal luminosity was found when the beams had large wakefield tails at the end of the linac. It was suggested that these wakefield dilutions were required to cancel some wakefield dilutions further downstream and this led to a study of the beam collimators [5].

Over the years, the SLC has installed a large number of collimators to reduce the backgrounds in the detector and this is also felt to be essential for a future linear collider. On inspection at the end of the 1994–95 run, it was found that many of these collimators were badly damaged. The collimators had been coated with a layer of gold to reduce the number of backscattered particles. Unfortunately the thermal contact between the goldl ayers and the body of the collimators was insufficient and the beam melted a very irregular channel through the gold [6]. This caused wakefields that were roughly 25–50 times larger than expected. Most of these damaged collimators were replaced for the 1996 run. To prevent similar damage, the replacement collimator jaws were coated with either vanadium or TiN. Both of these coatings have resistivities that are roughly 10 times larger than that of the gold but it was thought that they would have much better survival.

Measurements made during the 1996 SLC run [6] showed that the geometric component of the transverse wakefield was in agreement with the results of MAFIA calculations but the resistive wall wakefield of both the vanadium-coated collimators and the undamaged gold-coated collimators was roughly a factor of four higher than expected. The reasons for this discrepancy are still not explained and a facility is being planned at SLAC to test different collimator geometries and materials to gain further understanding [7].

Transverse Beam Jitter

Transverse beam jitter has two effects: it decreases the luminosity by decreasing the overlap of the two colliding beams and, more importantly, it makes the diagnostics more erratic and harder to interpret, thereby decreasing the effectiveness of the tuning procedures. During the 1994–1995 SLC run, many sources of transverse beam jitter were traced and eliminated [8]. Much of the jitter was found to arise from quadrupole vibrations induced by pressure surges in the cooling water system and vibrations from the water pumps. These were and are being corrected by modifying the quadrupole supports and the water pumps.

Another significant source of jitter on the electron beam was found to arise from the long-range transverse wakefield kicks due to the preceding positron beam. This source was reduced by changing the linac focusing lattice so that the electron and positron bunches have significantly different phase advances and thus the electron bunches are no longer driven resonantly by the positron beam [9].

Unfortunately, there still remains a 'white noise' source, that causes the vertical trajectory jitter to grow uniformly along the length of the linac by roughly $0.3\sigma_y$, whose source was undetermined. While damaging to SLC operation, this would also be a significant concern for NLC operation. There had been a number of candidates considered for this jitter, including dark current in the linac structures that drive transverse wakefields, higher-order correlations on the injected beam that then, due to the transverse wakefields, cause the motion of the bunch centroid to increase [10], and the more prosaic effect of 10% bunch length fluctuations [11] that arise from the sawtooth instability in the damping rings [12]. This later effect, where the variation of the bunch length changes both the loading due to the longitudinal wakefield and the deflections due to the transverse wakefields, describes the observed jitter well [13]. Measurements have confirmed that there is a high degree of correlation between the linac jitter and the sawtooth signal from the damping rings [10].

Sub-Micron Beam Diagnostics

Finally, additional diagnostic tools were commissioned including the 'laser wire' [14] which was installed inside the SLD detector. The laser wire is created by focusing an intense 349 nm laser to narrow spot, about 380 nm with a Rayleigh length of

5 μm. The e^-/e^+ beam is then scanned across the laser and the beam size is inferred from the rate of Compton backscattering. During the end of the 1996 SLC run, the laser wire was commissioned and found to have a width of 400–500 nm, roughly 20% greater than design but still more than sufficient for SLC operation. In the NLC, such devices will be needed throughout the linacs and final focus to measure the beam emittance.

Another important diagnostic is a technique of inferring the individual beam sizes at the IP using both the beam-beam deflection scans, which just yield the convoluted size of the two beams, and the BPMs to measure the energy loss of the outgoing beams [15]. This technique will be very important at the NLC where, at present, the beam-beam deflection is the only diagnostic capable of resolving the beam sizes at the IP.

NLC Design and R&D

The Next Linear Collider (NLC) [1, 2, 3] is a future electron/positron linear collider that is based on copper accelerator structures powered with 11.4 GHz X-band rf. It is designed to begin operation with a center-of-mass (cms) energy of 500 GeV (which could be decreased to 350 GeV to study the top quark) and to be adiabatically upgraded to 1 TeV cms. At the onset, the entire infrastructure will be constructed for the 1 TeV cms upgrade. The upgrade to 1.5 TeV could proceed either by a straightforward 50% extension of the linac length, a trombone is incorporated into the design to facilitate this extension, or by improvements in the rf technology, increasing the accelerating gradient; the final focus and collimation sections have been designed with sufficient length to facilitate the upgrade to 1.5 TeV cms.

The initial rf system for 500 GeV cms is based on components that have been developed or can be expected in the near future. Specifically, it is composed of 50 MW X-band klystrons, SLED-II rf pulse compressors, and Damped-Detuned accelerator Structures (DDS) that reduce the long-range transverse wakefields by a combination of weak damping and detuning of the dipole mode frequencies. The upgrade to 1 TeV is based on expected improvements in the rf technology and would proceed by replacing the 50 MW klystrons with 75 MW klystrons and doubling the number of modulators and klystrons.

The NLC design, shown schematically in Fig. 2, contains all of the components found in the SLC. There are sources, damping rings, and bunch compressors to produce the low emittance beams, long linacs to accelerate the beams to the desired energies, and collimation sections and final foci to produce the small spots needed at the IP. In this paper, we cannot describe the various components of the design and instead we refer to the recent design study that was completed and documented in the 'Zeroth-Order Design Report for the Next Linear Collider' [1]. This is a complete systems study with engineering support in crucial areas to verify feasibility.

The design incorporates many of the hard lessons from the SLC. Throughout the design, we have been careful to provide substantial operating margins on all the subsystems; if all of the subsystems perform as designed, then the luminosity would be roughly three times higher than that specified. In addition, the tolerances were specified to attain the design luminosity over a large range in operating parameters, such as bunch charge and beam emittance, and not just at a single point. Finally, the design includes extensive beam collimation sections and detailed diagnostic layouts and tuning procedures; all of these have been added onto the original SLC design as operational experience has been gained. The NLC design was reviewed by an external committee in March of 1996 and was presented to the 1996 DPF/DPB Snowmass meeting. At this time, a larger engineering effort is being started to further study the reliability issues as well as studying the issues associated with mass manufacture of components and, ultimately, producing a cost estimate and schedule.

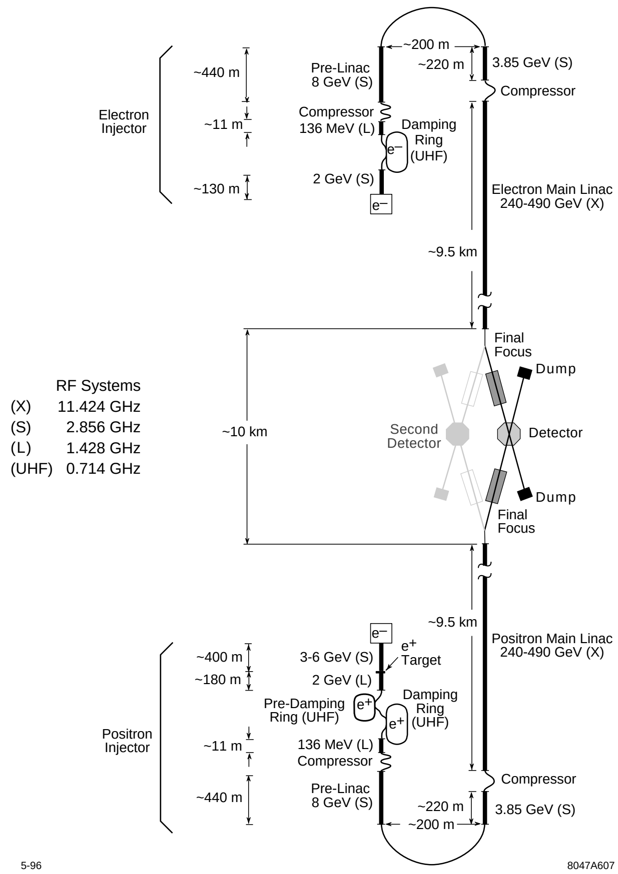

Figure 2: Schematic of the NLC; from Ref. [1].

As stated, detailed descriptions of the NLC design can be found elsewhere. In the next sections, we will describe some highlights of the ongoing R&D program that supports the NLC design.

Ground Motion Measurements

Because the NLC operates with low emittance beams which are focused to small spot sizes, there was concern that fast ground motion could cause beam jitter, leading to a significant loss in luminosity, while slower ground motion could prevent one from ever being able to properly align and tune the collider. Recent measurements at SLAC of the fast ground motion (0.01 Hz$<$

$f < 100$ Hz), using very high resolution seismographs, have confirmed the amplitude of the ground motion but have shown that the large amplitude motion is highly correlated [16]. Such motion has relatively little impact on the design and, with the exception of the final doublets which may need additional stabilization, the motion would not cause a significant $(> 2\%)$ source of luminosity loss. Of course, the design must be engineered carefully to ensure that any additional 'cultural' noise is minimized; measurements of the FFTB magnets at SLAC indicate that this is reasonable goal.

At much lower frequencies, it has been suggested that the ground has a diffusive behavior which can be described by the ATL rule [17]. This slow uncorrelated motion would cause the beam trajectory to drift with time requiring additional steering and tuning. Measurements of the motion of the magnets in the FFTB beamline at SLAC over a period of 180 hours found motions much smaller than previously reported [18]. This emphasizes the importance of site selection, although the FFTB tunnel could not be considered a quiet or ideal location. Finally, detailed simulations of the NLC linacs show that this slow ground motion should not significantly impede the operation of the collider [19].

Klystrons [20]

As described, the NLC will initially rely on 50 MW klystrons which will then be upgraded to 75 MW klystrons to achieve a full 1 TeV in the center-of-mass. At this time, the XL series of X-band klystrons are producing the required 50 MW pulses [21]. The latest klystron in the XL series, the XL4, produces 75 MW with an efficiency of 48%. The tube is very robust with stable output power and an infrequent fault rate. Furthermore, the performance of the XL series has been in close agreement with the simulation results giving confidence in our ability to design klystrons with the aid of computer simulation.

Unfortunately, the XL klystrons all use solenoidal focusing and these solenoids are both expensive and consume a significant amount of power. Thus, a Periodic Permanent Magnet (PPM) focused klystron, shown schematically in Fig. 3, has been developed [22]. In initial tests just completed, this klystron produced 1.5 μs pulses of 52 MW at 55% efficiency; this exceeds the requirements for the NLC. In addition, the klystron produced 300 ns pulses of 60 MW at 63% efficiency. At the higher power, the length of the pulse was limited due to rf breakdown and thus the klystron has been opened and the cavities are being coated with TiN. The next PPM klystron is being designed to produce 75 MW which will meet the requirements for the 1 TeV cms NLC upgrade.

Damped-Detuned Accelerator Structures [23]

To control beam-breakup of the long bunch trains in the NLC linacs, the long-range transverse wakefields in the accelerator structures must be reduced. This is done by acombination of detuning the dipole modes so that there is a $\sim$10% Gaussian spread in the frequencies, causing the dipole modes to rapidly decohere, and damping the dipole modes with Q's of roughly 1000 to prevent the modes from recohering at a later time. The damping is added to the Damped-Detuned Structures (DDS) by coupling each cell to four manifolds running along the length of the structures as illustrated in Fig. 4. Recent measurements of the transverse wakefields in the DDS structures, which were in excellent agreement with theory, showed that the wakefield is damped below the limit required for the NLC [23]; additional optimization of the matching into the manifold loads should reduce the wakefields even further.

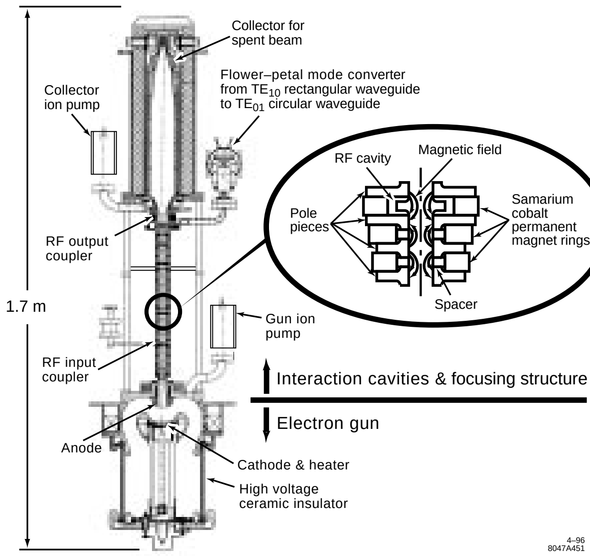

Figure 3: Schematic of PPM klystron; from Ref. [1].

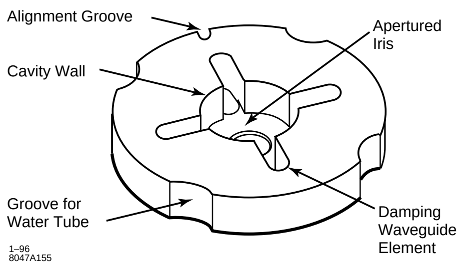

Figure 4: Schematic DDS structure; from Ref. [1].

The four damping manifolds also provide a straightforward method of measuring the induced dipole modes. In the NLC, the accelerator structures, which will be mounted on remote movers, need to be aligned to the beam trajectory by minimizing these measured dipole mode signals with high resolution. Furthermore, because the frequencies of the dipole modes vary along the length of the structure, one can determine what portion of the structure is misaligned. This technique was tested during the recent wakefield measurements [24]. The analysis of the resolution was complicated by a very large kink in the structure due to an unfortunate construction error. Regardless, the measurements reproduced the measured alignment, including the kink. Further analysisis required but the initial results look extremely promising.

NLC Test Accelerator [26]

The NLC Test Accelerator (NLCTA) [25] is designed to both test all of the rf components required for the NLC and to verify the beam loading compensation technique that is needed to control the energy spread along the NLC bunch train. It consists of a 70 MeV X-band injector, a magnetic chicane, and six 1.8 m X-band (11.4 GHz) accelerator structures that are designed to suppress the long-range transverse wakefields. The X-band injector and the six main accelerator structures will be powered with four 50 MW X-band klystrons, whose peak power is compressed with SLED-II pulse compressors, producing a 50 MV/m acceleration gradient.

At this time, the entire NLCTA beamline, except for the six accelerator structures, has been installed and is under vacuum. Beam from the gun has been accelerated to 60 MeV in the injector and transported to the final dump. Commissioning will begin this fall as the additional klystrons and accelerator structures are installed [26].

Conclusions

Although the 1996 SLC/SLD physics run did not deliver the luminosity expected, the SLD detector commissioned a new vertex chamber, the VXD3, and the run yielded a lot of useful accelerator physics. Many performance limitations were understood, giving important information for both SLC and future linear colliders. This includes experiments on beam-based feedback, collimator wakefields, a determination of the 'anomalous' jitter, and the laser wire.

Recently, a design study for the NLC was completed and documented in the 'Zeroth-Order Design Report for the Next Linear Collider.' This is a complete systems study with engineering support in crucial areas to verify feasibility. This design incorporates many of the hard lessons from the SLC and was both reviewed by an external committee in March of 1996 and presented to the 1996 DPF/DPB Snowmass meeting. At this time, a larger engineering effort is being started to estimate a cost and schedule.

In addition, the NLC R&D program has yielded very impressive results including the PPM klystron which exceeded the efficiency requirements and performed almost exactly as predicted, the DDS accelerator structure which also performed very close to expectations, and the extensive ground motion studies, which show that the highly correlated nature of the ground motion significantly reduces its impact and would cause minimal luminosity loss. Finally, the NLCTA, which is a model of the NLC linac and will verify the entire NLC rf system, is being commissioned.

Although this paper has concentrated on the SLC results and the NLC design, it must be emphasized that this is a really exciting time for all the future linear collider designs. Many of the test facilities, that have been designed to demonstrate the required technology for the different designs, are or will be commissioned soon. As these tests are completed, the next big challenge will be to complete fully engineered cost estimates for designs with the required reliability and operating margin to ensure successful operation.

References

[1] NLC ZDR Design Group, SLAC Report 474 (1996).

[2] NLC ZDR Design Group and the NLC Physics Working Group, SLAC Report 485 (1996).

[3] *Proc. of the 1996 DPF/DPB Workshop: New Directions for High Energy Physics,* Snowmass, CO (1996).

[4] L. Hendrickson, *et. al., Proc. of the 1995 Part. Acc. Conf.,* Dallas, TX (1995), p. 2389.

[5] K. Bane, *et. al., Proc. of the 1995 Part. Acc. Conf.,* Dallas, TX (1995), p. 3031.

[6] F.J. Decker, *et. al.,* 'Design and Performance of the New SLC Collimators,' *these proceedings,* Geneva, Switzerland (1996).

[7] D. Walz, private communication (1996).

[8] C. Adolphsen, *et. al., Proc. of the 1995 Part. Acc. Conf.,* Dallas, TX (1995), p. 646.

[9] F.J. Decker, *et. al.,* 'Long-range Wakefields and Split-Tune Lattice at the SLC,' *these proceedings,* Geneva, Switzerland (1996).

[10] F.J. Decker, *et. al.,* 'Higher Order Beam Jitter in the SLC Linac,' *these proceedings,* Geneva, Switzerland (1996).

[11] B. Podobedov, R. Siemann, private communication (1996).

[12] K. Bane, *et. al., Proc. of the 1995 Part. Acc. Conf.,* Dallas, TX (1995), p. 3109.

[13] R. Assmann and F. Zimmermann, 'Possible Sources of Pulse-to-Pulse Orbit Variation in the SLAC Linac,' *these proceedings,* Geneva, Switzerland (1996).

[14] M. Ross, *et. al.,* 'A High Performance Spot Size Monitor,' *these proceedings,* Geneva, Switzerland (1996).

[15] P. Raimondi, private communication (1996).

[16] C. Adolphsen, *et. al.,* to be published (1996); also see Appendix C of Ref. [1].

[17] V. Parkhomchuk, *et. al., Part. Acc.,* **46:** 241 (1994).

[18] R. Assmann, *et. al.,* 'Beamline Stability Measurements with a Stretched Wire System at the FFTB,' *these proceedings,* Geneva, Switzerland (1996).

[19] R. Assmann, *et. al.,* 'Emittance Dilution due to Slow Alignment Drifts in the Main Linacs of the NLC,' *these proceedings,* Geneva, Switzerland (1996).

[20] P. Wilson, 'Advanced RF Power Sources for Linacs,' *these proceedings,* Geneva, Switzerland (1996).

[21] G. Caryotakis, *Proc. 3rd Int. Work. on RF Pulsed Power Sources of Linear Colliders,* Hayama, Japan (1996).

[22] D. Sprehn, *et. al., Proc. 3rd Int. Work. on RF Pulsed Power Sources of Linear Colliders,* Hayama, Japan (1996).

[23] R.H. Miller, *et. al.,* 'A Damped-Detuned Structure for the Next Linear Collider,' *these proceedings,* Geneva, Switzerland (1996).

[24] M. Seidel, *et. al.,* 'Microwave Analysis of the Damped-Detuned Accelerator Structure,' *these proceedings,* Geneva, Switzerland (1996).

[25] R. Ruth, *et. al.,* SLAC Report 411 (1993).

[26] R. Ruth, *et. al.,* 'Status and Results from the Next Linear Collider Test Accelerator,' *these proceedings,* Geneva, Switzerland (1996).