SLAC-PUB-95-6742

# RF Pulse Compression in the NLC Test Accelerator at SLAC*

Theodore L. Lavine

*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309*

**Abstract.** At the Stanford Linear Accelerator Center (SLAC), we are designing a Next Linear Collider (NLC) with linacs powered by X-band klystrons with rf pulse compression. The design of the linac rf system is based on X-band prototypes which have been tested at high power, and on a systems-integration test—the Next Linear Collider Test Accelerator (NLCTA)—which is currently under construction at SLAC. This paper discusses some of the systems implications of rf pulse compression, and the use of pulse compression in the NLCTA, both for peak power multiplication and for controlling, by rf phase modulation, intra-pulse variations in the linac beam energy.

## INTRODUCTION

The demand for high peak power and high pulse-repetition rate in future linear colliders poses significant challenges for development of linac rf systems with stable, reliable, cost-effective, and efficient rf sources. At the Stanford Linear Accelerator Center (SLAC), we are designing a Next Linear Collider (NLC) with linacs powered by X-band klystrons with rf pulse compression. The design is based on experience building and operating the Stanford Linear Collider (SLC) and its associated Final Focus Test Beam (FFTB) with 50-GeV beams, on X-band rf prototypes which have been tested at high power, and on an rf systems-integration test—the Next Linear Collider Test Accelerator (NLCTA)—which is currently under construction at SLAC. The NLC baseline design will have linac beam energies of 250 GeV, and will be compatible with a future upgrade to beam energies of at least 500 GeV. This paper discusses some of the systems implications of rf pulse compression, and the use of pulse compression in the NLCTA, both for peak power multiplication and for controlling, by rf phase modulation, intra-pulse variations in the linac beam energy.

* Work supported by Department of Energy contract DE-AC03-76SF00515.

*Presented at the Conference on Pulsed RF Sources for Linear Colliders, Montauk, Long Island, New York, October 2–7, 1994*

## RF SYSTEM EFFICIENCY

In a linear collider rf system that is optimized with respect to construction and operating costs, the number and characteristics of the rf sources depend greatly on whether or not rf pulse compression is employed. With rf pulse compression, the peak power demand on the klystrons (or other rf sources) is relaxed, permitting reduced perveance ($IV^{-3/2}$). Significant benefits of the reduced-perveance of the rf sources include: operation at conventional high voltage levels (less than 600 kV), increased electronic efficiency (possibly greater than 60%), and use of fully-efficient focusing by periodic arrays of permanent magnet lenses,[2] as is planned by SLAC's klystron-development group.

The increased rf pulse duration required for rf pulse compression permits a significant increase in the energy-transfer efficiency of the dc pulse modulators used with the rf sources because, as the modulator pulse duration is increased, the rise and fall times comprise a smaller fraction of the total modulator pulse. This is a significant effect:[3] The energy per unit time wasted during the rise and fall of the pulse is approximately half of the energy per unit time in the flat-top part of the pulse. The energy in the rise is roughly equal to the energy in the fall. The rise time is roughly proportional to the square root of the modulator's equivalent-energy pulselength, which is approximately $T_{flat}+(T_{rise}+T_{fall})/2 \approx T_{flat}+T_{rise}$. For the specific example[4] of a fast-risetime NLC-compatible modulator design incorporating a multiplying Blumlein pulse-forming network, the flat-top duration is 1.25 μs, the rise time is 0.27 μs, the fall time is 0.40 μs, and the corresponding efficiency of energy transfer from the pulse-forming network through the pulse transformer to the flat-top portion of klystron pulse is about 80%. (The net efficiency of the modulator also includes a factor for the transfer of energy from the ac line to energy stored in the capacitors of the pulse-forming network, which is typically approximately 95% efficient.)

In general, there is a trade-off between the peak-power gain achieved by pulse compression and the efficiency of the pulse compressor. For SLED[5] and SLED-II pulse-compression systems,[6] the trade-off is shown in Figure 1.[7] The inherent inefficiency of SLED-type pulse compressors is the result of the inability to completely discharge SLED energy storage cavities, or SLED-II resonant delay

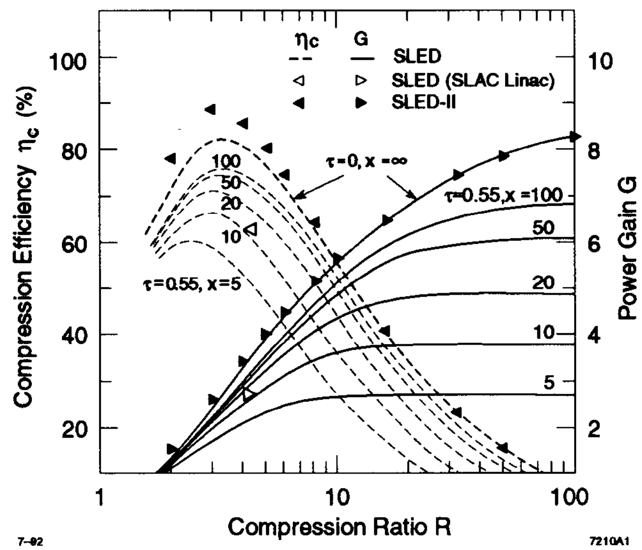


FIGURE 1. Power gain (solid curves) and compression efficiency (dashed curves) for a SLED-II rf pulse compressor driving an accelerator structure with $\tau$ and x as indicated. $\tau$ is the voltage attenuation parameter (nepers) for the structure. x is the unloaded time constant of the pulse-compression energy-storage cavities ($2Q/\omega$) normalized to the structure filling time. The top curves show gain and efficiency for SLED as implemented for the SLAC linac. The solid triangular points are for a SLED-II system with lossless components.

lines, in a finite time. Hence, a SLED-II pulse-compression ratio of five is at most 80% efficient.

The conceptual design currently favored at SLAC for a 500-GeV center-of-mass linear collider includes 50-MW, X-band klystrons with 1.25-μs pulse duration, and SLED-II rf pulse compression by a factor of five.[8] Efficiency goals for the pulse modulators, klystrons, pulse compressors, and rf power transmission, respectively, are 75%, 60%, 76%, and 95%. The net efficiency product is 32%.

## THE NLC TEST ACCELERATOR PROJECT

The Next Linear Collider Test Accelerator (NLCTA) is currently under construction at SLAC. The goals of the NLCTA project[9,10] are to integrate the new technologies of X-band accelerator structures and high-power rf systems being developed for the Next Linear Collider, to measure the growth of the "dark current" generated by rf field emission in the accelerator, to demonstrate multi-bunch beam-loading energy compensation and suppression of higher-order beam-deflecting modes, and to measure any transverse components of the accelerating field. These goals will reduce the technical risk of a future X-band linear collider project, and will aid in understanding the cost of such a project. The NLCTA parameters are summarized in Table 1.

**TABLE 1.** NLCTA Design Parameters

| | Parameter | Design | Upgrade |
|---|---|---|---|
| Beam | Electrons per bunch | $0.4 \times 10^9$ | $6.5 \times 10^9$ |
| | Bunch frequency | 11.424 GHz | 0.714 GHz |
| | Bunches per pulse | 1440 | 90 |
| | Pulse length | 0.125 μs | |
| | Beam pulse repetition rate | 10 Hz | |
| Accelerator | Accelerating gradient, unloaded | 50 MV/m | 85 MV/m |
| | Accelerating gradient, full current | 37 MV/m | 64 MV/m |
| | Filling time | 0.1 μs | |
| | Section length | 1.8 m | |
| | Sections per module | 2 | |
| | Modules in linac | 3 | |
| RF Pulse Compression | Compressed rf pulse length | 0.25 μs | |
| | Compression ratio | 6 | |
| | Efficiency (inherent x components) | $0.75 \times 0.90 = 0.67$ | |
| | Peak power gain | 4 | |
| RF Transmission | Efficiency | 0.86 | |
| Klystrons | Klystrons per module | 1 | 2 |
| | Peak rf power per klystron | 50 MW | 75 MW |
| | Klystron pulse length | 1.5 μs | |
| | Voltage | 400 kV | 540 kV |
| | Perveance | 1.2 $\mu A/V^{3/2}$ | 0.6 $\mu A/V^{3/2}$ |
| | Electronic efficiency | 0.45 | 0.60 |
| | Rf pulse repetition rate | 180 Hz | 120 Hz |

The NLCTA high-power rf system is depicted schematically in Figure 2. The NLCTA linac is composed of an X-band accelerator structure in 1.8-meter-long sections with 0.1-µs filling time. (The injector contains two 0.9-m X-band sections in order to maintain beam loading comparable to the linac in the presence of greater current). All the X-band sections will suppress transverse wakefields, either by cell-to-cell detuning,[11] or by a combination of detuning and damping.[12] The effect of detuning has been demonstrated experimentally with the prototype 1.8-m detuned X-band section by using positron and electron bunches from the SLC damping rings as probe and witness beams, respectively.[13]

The high-power rf source for the NLCTA is the 50-MW, X-band klystron developed at SLAC.[14] Thus far, two prototype tubes have been built and operated at 50-MW peak power for the required 1.5-µs pulse duration at 60 pulses per second.

Rf pulse compression in the NLCTA will be performed by the SLED-II technique. A prototype SLED-II system has been tested at SLAC with an X-band klystron in order to validate the design of the NLCTA pulse-compression system and its components.[15] Power from the SLED-II prototype was used to achieve the desired 50-MV/m accelerating gradient in the prototype NLCTA 1.8-m accelerating section, in the Accelerator Structure Test Area[16,17] at SLAC.

To achieve low rf losses, oversized circular waveguide will be used for the SLED-II delay lines and for the transmission lines that carry the rf from klystron to SLED-II, and from SLED-II to the accelerator. The $TE_{01}$ mode will be propagated in the circular waveguide. Matching to the $TE_{10}$ mode in rectangular waveguide will be performed by compact, low loss mode transducers.[18]

The NLCTA rf system has been designed so as to accomodate the possibility of a future upgrade which would increase the accelerating gradient by 70% by replacing each 50-MW klystron with a pair of 75-MW klystrons. The pulse modulators each are being sized to accomodate a pair of 75-MW tubes.

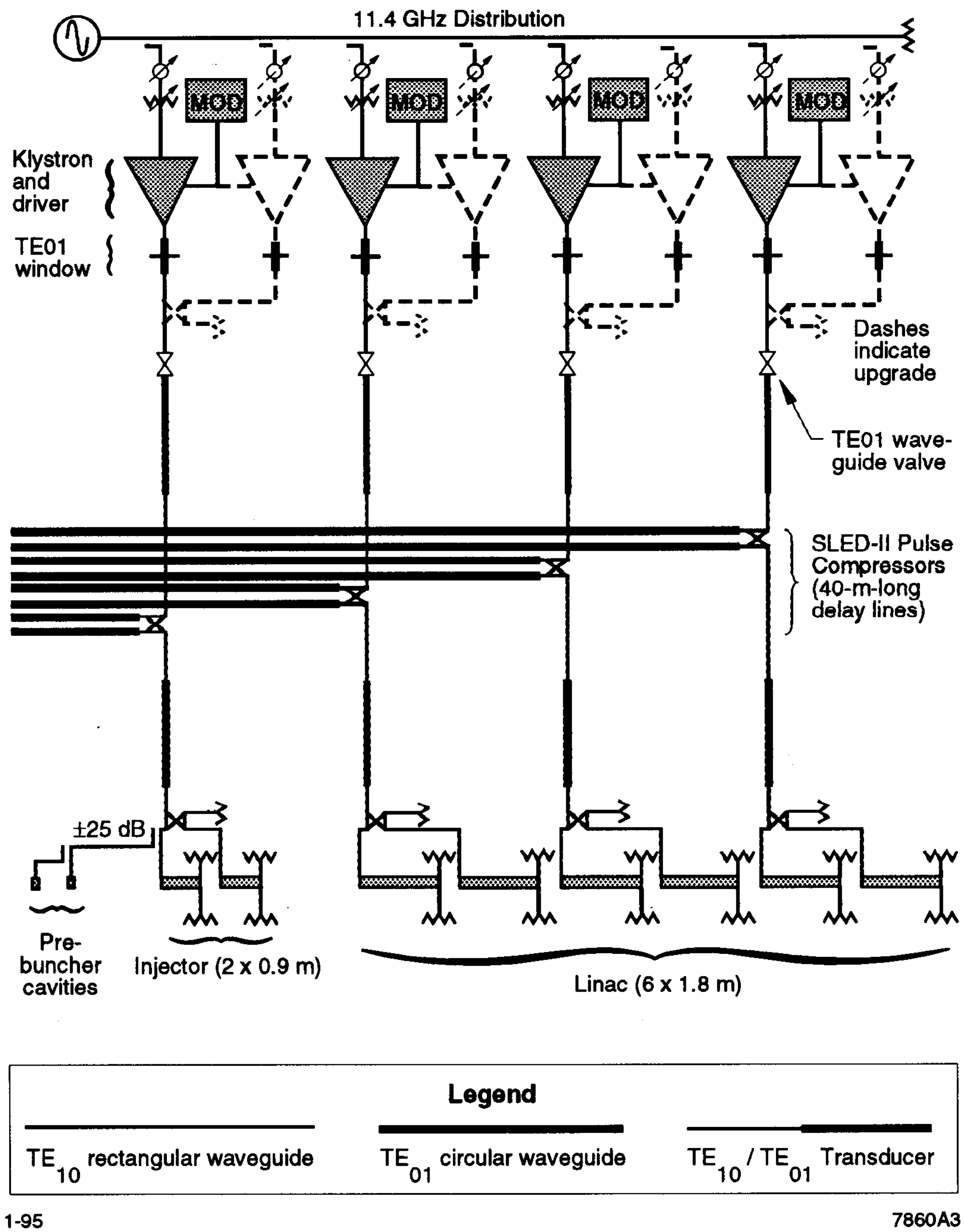


**FIGURE 2.** Schematic layout of the NLCTA high-power rf system.

## RF Pulse Compression and Intra-Pulse Energy Control

The intra-pulse energy variation of the linear collider beams must be small, typically a few tenths of a percent. Rf pulse compression provides a useful technique for precise intra-pulse beam-energy control with stable phase, which will be tested using the NLCTA.

Using pulse compression on the output of a klystron in saturation, it is possible to produce an amplitude-modulated, phase-stable, high-power compressed pulse. The technique, illustrated in Figure 3, involves modulating the phase of the low-level rf drive in piecewise segments such that, after the rf is amplified by the saturated klystron and the sequential pieces are combined by the pulse compressor, the imaginary parts of the phasors cancel and the real parts add constructively.[19]

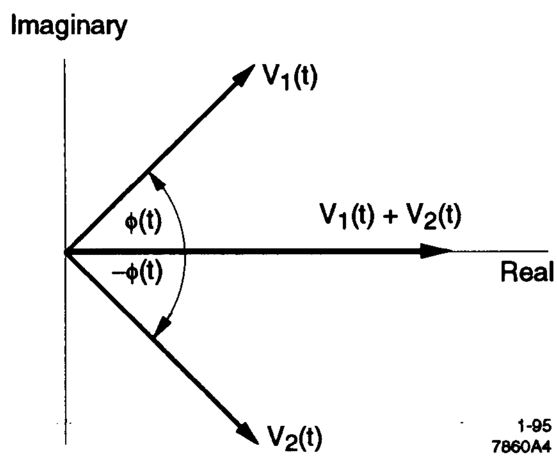


**FIGURE 3.** If two segments of an rf pulse are modulated oppositely in phase, then, during pulse compression, the real components of their phasors add constructively and the imaginary components cancel. This technique permits a pulse compressor to transform phase modulation into amplitude modulation.

This technique provides a method for transient beam-loading compensation in long (multi-bunch) beam pulses. In this case, the phase of the low-level rf drive for a saturated klystron can be modulated at 200-MHz bandwidth so as to modulate the klystron output amplitude at constant phase. In the beam-loading compensation scheme being developed for the NLCTA, the rf will be ramped from 30% to 100%

of its peak voltage during one filling time (0.1 μs) prior to the passage of the beam through the accelerator structure, and then will remain at 100% voltage for the remainder of the pulse. The resulting distribution of rf in the accelerator is expected to suppress to approximately 0.1% the transient loading of the beam pulse which, if uncompensated would result in a 25% energy depression one filling time into the beam pulse. Two low-level rf phase-modulation schemes for producing flat and ramped compressed pulses, respectively, are illustrated in Figure 4.[20] A simulation of the compensating effect of the ramped scheme (Figure 4b) on transient beam loading is shown in Figure 5.[21]

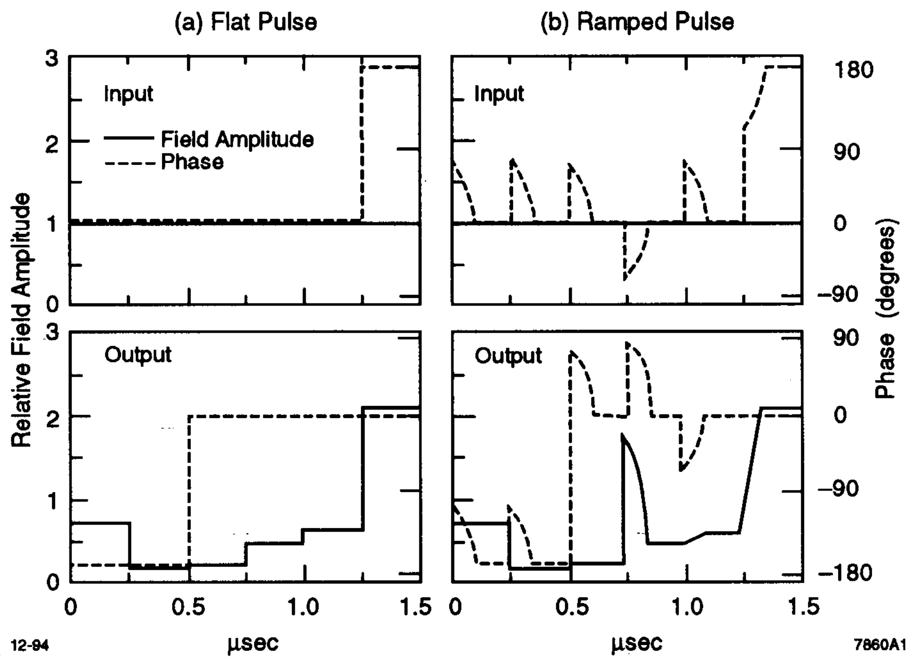


**FIGURE 4.** Two low-level rf phase modulation schemes for producing compressed pulses that are (a) flat and (b) ramped, using SLED-II. In both cases, the compressed pulse appears during the time interval from 1.25 μsec to 1.5 μsec after the start of the klystron rf pulse. The beam enters the accelerator structure at 1.35 μsec.

The same low-level rf phase-modulation technique—with a bandwidth of several megahertz—will be exploited in the NLCTA to compensate the intra-pulse beam-energy variation that will result from modulator voltage ripple.

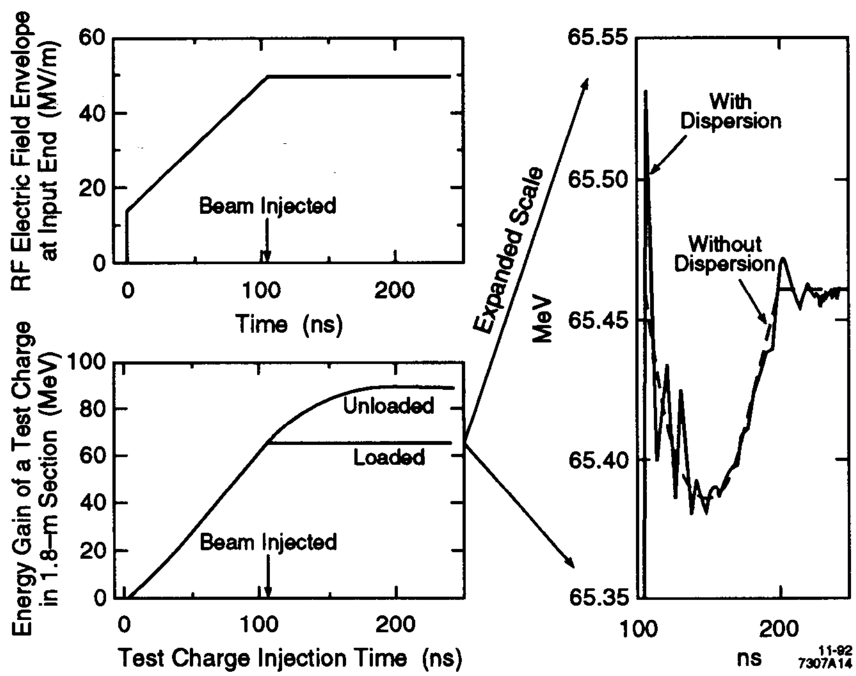


**FIGURE 5.** Simulation of the compensating effect of the ramped-pulse scheme (of Figure 4b) on transient beam loading. In this Figure, time is measured relative to the beginning of the compressed rf pulse.

## NLCTA Schedule

The high-power rf system for the NLCTA injector (modulator, klystron, pulse compressor, and two 0.9-m-long X-band accelerator sections) is currently being fabricated. High-power testing of the injector is planned in Summer 1995. Two of the three linac rf systems (two modulators, two klystrons, two pulse compressors, and four 1.8-m-long X-band accelerator sections) will be installed and ready for high-power tests in Summer 1996. The first accelerator physics experiments are planned for 1996–1997. We plan to install the last linac rf system (including the fifth and sixth 1.8-m-long X-band sections) in 1997.

## ACKNOWLEDGEMENTS


Development of SLED-II pulse compression, the high-power prototype, and the plans for beam energy control and stabilization, are the results of significant contributions by R. Callin, K. Fant, Z. D. Farkas, C. Galloway, H. Hoag, R. Jones, K. Ko, N. Kroll, T. Lavine, T. G. Lee, R. Loewen, A. Menegat, R. H. Miller, C. Nantista, C. Pearson, R. Ruth, S. Tantawi, K. Thompson, A. Vlieks, J. Wang, P. B. Wilson, and C. Yoneda. The efforts of NLCTA engineers, R. Pope and J. Rifkin, to design and construct the NLCTA high-power rf system, are also gratefully acknowledged.

## REFERENCES

[2]Eppley, K. R., "A PPM Focused Klystron at X-Band with a Travelling Wave Output Structure" (SLAC-PUB-6689), in these proceedings.

[3]Wilson, P. B., "Application of High-Power Microwave Sources to TeV Linear Colliders" (in *Applications of High-Power Microwaves,* edited by A. V. Gaponov-Grekhov and Victor L. Granatstein, Artech House, Boston, 1994), pp. 287–290.

[4]*Ibid.*

[5]Farkas, Z. D. *et al.*, "SLED: A Method of Doubling SLAC's Energy" (SLAC-PUB-1453), in Proceedings of the 9th International Conference on High Energy Accelerators (Stanford, California, May 2–7, 1974), pp. 576–583.

[6]Wilson, P. B., Farkas, Z. D., and Ruth, R. D., "SLED-II: A New Method of RF Pulse Compression" (SLAC-PUB-5330), in Proceedings of the 1990 Linear Accelerator Conference, Albuquerque, New Mexico, September 10–14, 1990.

[7]From Wilson, P. B. *et al.*, "Progress at SLAC on High-Power RF Pulse Compression" (SLAC-PUB-5866), in Proceedings of the 15th international Conference on High Energy Acccelerators (Hamburg, Germany, July 20–24, 1992).

[8]Wilson, P. B., NLC Note #1 (SLAC Internal Report), August 1994.

[9]"Next Linear Collider Test Accelerator Conceptual Design Report," SLAC Report 411 (SLAC, August 1993).

[10]Ruth, R. D. *et al.*, "The Next Linear Collider Test Accelerator" (SLAC-PUB-6252), in Proceedings of the 1993 IEEE Particle Accelerator Conference (Washington, DC, May 17–20, 1993), pp. 543–545.

[11]Thompson, K. A. *et al.*, "Design and Simulation of Accelerating Structures for Future Linear Colliders" (SLAC-PUB-6032), submitted to *Particle Accelerators.*

[12]Kroll, N. *et al.*, "Higher-Order Mode Damping for a Detuned Structure" (SLAC-PUB-6624), in Proceedings of the 17th International Linear Accelerator Conference, Tsukuba, Japan, August 21–26, 1994.

[13]Adolphsen, C. *et al.*, "Measurement of Wakefield Suppression in a Detuned X-Band Accelerator Structure," in Proceedings of the 17th International Linear Accelerator Conference, *loc. cit.*

[14]Wright, E. L. *et al.*, "Design of a 50-MW Klystron at X-Band" (SLAC-PUB-6676), in these proceedings.

[15]Nantista, C. *et al.*, "High Power RF Pulse Compression with SLED-II at SLAC" (SLAC-PUB-6145), in Proceedings of the 1993 IEEE Particle Accelerator Conference, *loc. cit.*, pp. 1196–1198.

[16]Vlieks, A. E. *et al.*, "Accelerator and RF System Development for NLC" (SLAC-PUB-6148), in Proceedings of the 1993 IEEE Particle Accelerator Conference, *loc. cit.*, pp. 620–622.

[17]Wang, J. W. *et al.*, "High Gradient Tests of SLAC Linear Collider Accelerator Structures" (SLAC-PUB-6617), in Proceedings of the 17th International Linac Conference, *loc. cit.*

[18]Tantawi, S., Ko, K., and Kroll, N., "Numerical Design and Analysis of a Compact $TE_{10}$ to $TE_{01}$ Mode Transducer" (SLAC-PUB-6085), in Proceedings of the Computational Accelerator Conference, Pleasanton, California, February 22–26, 1993.

[19]Nantista, C. D., "Ramping SLED-II for Beam-Loading Compensation," NLCTA Note #27 (SLAC Internal Report), August 19, 1994.

[20]*Ibid.*

[21]From "NLC Test Accelerator Conceptual Design Report," *op. cit.*, pp. 32–33.