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RESEARCH AT SLAC TOWARDS THE NEXT LINEAR COLLIDER*

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INTRODUCTION

The purpose of this paper is to review the ongoing research at SLAC towards the design of a next-generation linear collider (NLC). The energy of the collider is taken to be 0.5 TeV in the CM with a view towards upgrading to 1.0 or 1.5 TeV. The luminosity is in the range of 10^{33} to 10^{34} $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$. The energy is achieved by acceleration with a gradient of about a factor of five higher than SLC, which yields a linear collider approximately twice as long as SLC. The detailed trade-off between length and acceleration should be based on total cost and upgrade possibilities. A very broad cost optimum occurs when the total linear costs equal the total cost of RF power.

The luminosity of the linear collider is obtained basically in two ways. First, the cross-sectional area of the beam at the interaction point is decreased primarily by decreasing the vertical size. This creates a flat beam and is useful for controlling beamstrahlung. Secondly, several bunches (~10) are accelerated on each RF fill in order to more efficiently extract energy from the RF structure. This effectively increases the repetition rate by an order of magnitude.

An overall layout of the collider is shown in Fig. 1. In the next several sections, we trace the beam through the collider to review the research program at SLAC. More details of ongoing work at SLAC and throughout the world can be found in Refs. 1-5.

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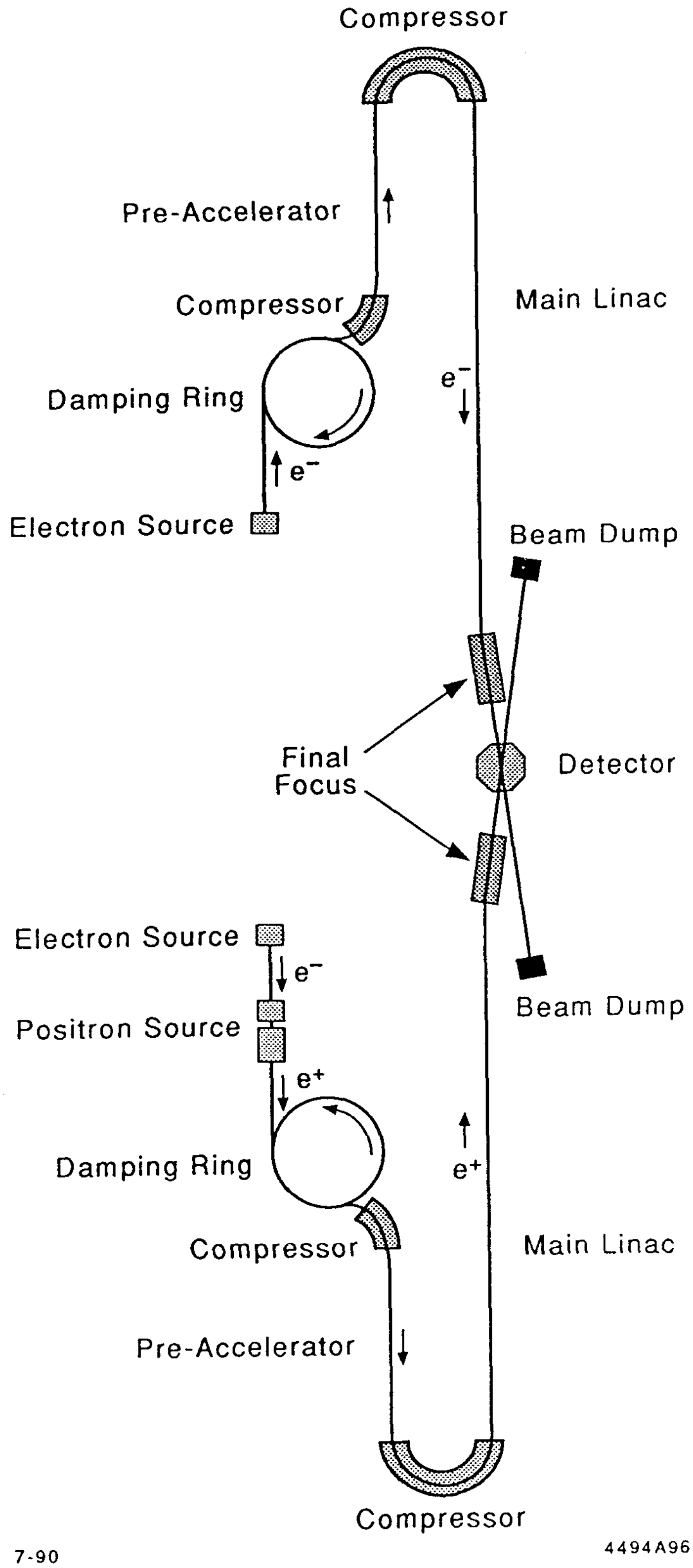

Fig. 1. Schematic of a Next Linear Collider.

NLC PARAMETER OPTIONS

We have recently reviewed several options for an NLC which has an initial energy of 0.5 TeV in the CM and an upgraded energy of 1.0–1.5 TeV. Table 1 lists three parameter options: the first two columns are for 0.5 TeV in the CM, while the final column is for 1.0 TeV. In Option 1, a short linear collider is constructed with the full acceleration gradient of 100 MV/m. This can be upgraded to Option 3 by doubling the length of the linac while keeping the injection system fixed. In Option 2, a long linear collider is constructed with a reduced acceleration gradient of 50 MV/m. This can be upgraded to Option 3 by the addition of power sources to the linac. In both upgrade paths, the final focus must be modified somewhat.

Table 1. NLC Parameter Options.

		1	2	3
Energy		$\frac{1}{4}+\frac{1}{4}$ TeV	$\frac{1}{4}+\frac{1}{4}$ TeV	$\frac{1}{2}+\frac{1}{2}$ TeV
Luminosity		2×10^{33}	2×10^{33}	1×10^{34}
Linac Length		7 km	14 km	14 km
Accel. Gradient		100 MV/m	50 MV/m	100 MV/m
RF Frequency		11.4 GHz	11.4 GHz	11.4 GHz
#Particles/bunch:	DR	2×10^{10}	1×10^{10}	2×10^{10}
	Linac	1.8×10^{10}	9×10^{9}	1.8×10^{10}
	FF	1.5×10^{10}	7×10^{9}	1.5×10^{10}
# bunches, n_b		10	10	10
Repetition Freq.		120 Hz	180 Hz	180 Hz
Wall Plug Power		66 MW	50 MW	200 MW
IP Beam Size:	σ_y	4 nm	4 nm	2.5 nm
	σ_x	320 nm	200 nm	220 nm
	σ_z	100 μm	100 μm	100 μm

Option 1 is quite short and may be less expensive than Option 2, but we are required to face all the problems of the high acceleration gradient and the required high peak power RF sources. In Option 2, we relax the requirements for RF power by a factor of four and begin with an acceleration gradient which will generate much less dark current. The price is an initially longer accelerator with the increased conventional construction.

We have found in the design process that it is very important to realize that the intensity and emittance at the final focus are quite different than those in the damping ring. To model this, the intensity has been allowed to decrease as shown in Table 1. In addition, the emittance at the final focus is assumed to be diluted by about 65%.

DAMPING RINGS & BUNCH COMPRESSION

Initial designs for damping rings and bunch compression systems have been completed and are discussed in Refs. 6-9. The emittances required are an order of magnitude smaller than those achieved at the SLC. In addition, the design exploits the natural asymmetrical emittances of electron storage rings with $\epsilon_x/\epsilon_y = 100$. The rings are about five times the circumference of the SLC ring and have a design energy of 1.8 GeV. The damping time to achieve 360 Hz is obtained through the use of wigglers in straight sections; however, if the repetition rate is dropped to 180 Hz, as in Table 1, these wigglers can probably be eliminated from the design. Alternatively, the higher repetition rate could be used to double the luminosity.

The bunch length in the damping ring is about 5 mm. In order to reduce transverse wakefields in the high gradient linac and also to keep the bunch length less than the depth of focus at the IP, we must compress the bunch to less than 100 μm. As discussed in Refs. 8 and 9, this is achieved by using two compressors separated by a pre-accelerator linac. This combination serves to reduce the bunch length by two orders of magnitude, while keeping the relative energy spread below about 1%. The second compressor may also be used to bend the beam by 180° as shown in Fig. 1. This bend is useful for possible upgrades in length and also allows the use of direct feedback to control injection jitter in the linac.

LINAC

The linac is envisioned to be similar to the SLAC disk-loaded structure with a frequency of four times the present SLAC frequency. The irises in the design are somewhat larger (relative to the wavelength) to reduce transverse wakefields. The structure will have other modifications to damp long-range transverse wakefields. This will be driven by a power source capable of about 220 MW/m in order to obtain an accelerating field of up to 100 MV/m.

The remainder of this section is divided into three subsections. In the first subsection we discuss structures, the second deals with RF power sources, and the third treats emittance preservation.

Structures

The first question that arises for the RF structure is breakdown. This question is treated in Refs. 10 and 11, where G. Loew and J. Wang present results from many experiments at various frequencies. If the scaling laws thus obtained are extrapolated to 11.4 GHz, the breakdown-limited surface fields obtained are 660 MV/m. To convert this to an effective accelerating gradient, a reduction factor of 2.5 is typically used, which yields an accelerating gradient above 200 MeV/m. However, the measurements also indicated significant "dark currents" generated by captured field-emitted electrons. The question of the effects of dark current on loading and beam dynamics is not yet resolved and may provide the ultimate limit to the acceleration gradient.

As mentioned in the Introduction, in order to make efficient use of the RF power and to achieve high luminosity, it seems essential to accelerate a train of bunches with each fill of the RF structure. This leads to two problems: the energy of the bunches in the train must be controlled, and the transverse stability of the bunch train must be ensured.

The problem of energy control is studied in Ref. 12. Provided that the higher longitudinal modes are damped, it seems possible to extract up to about 25% of the energy in the structure while still maintaining a small bunch-to-bunch energy spread. Transverse effects are treated in Refs. 13 and 14. The most severe problem is beam breakup in the linac; however, if the transverse modes are damped to Q's $\sim$ 10–50 and (with the higher Q's) if the first dipole mode can be tuned, then there is no beam breakup in the linac. Thus, both problems can be solved by damping higher modes (both transverse and longitudinal) in the RF structure.

In Ref. 15, R. Palmer describes a technique of using slotted irises coupled to radial waveguides to damp these modes: Q's as low as 10–20 were measured in model structures. This encouraging evidence has led to a development program at SLAC to do more detailed studies of slotted structures.

Recently at SLAC, Q's as low as 8 have been measured in low-power models at 2.8 GHz.[16,17] Several different techniques are being explored and experiments are also ongoing at high frequency.[16]

In addition, there is new evidence that an alternative to damping the structures is to detune each structure cell to cell. This spread in frequency leads to a decoherence of the wakefield which yields an effective damping. This technique is presently under study at SLAC.

RF Power Sources

Before discussing results on power sources, it is useful to contrast and compare two basic approaches, RF pulse compression and magnetic pulse compression.

<u>RF pulse compression and conventional klystrons</u>: Prior to RF pulse compression, a long modulator pulse is converted by a high-power, "semi-conventional" klystron or some other power source into RF power with the same pulse width. This RF pulse can then be compressed by slicing the pulse using phase shifts and 3 db hybrids and re-routing the portions through delay lines, so that they add up at the end to a high peak power but for a small pulse width. This scheme was invented by D. Farkas at SLAC and is presently under experimental investigation.[18] With a factor of 6 in pulse compression, a 100 MW klystron could power about 3 m of structure to achieve an accelerating gradient of about 100 MV/m.

In Ref. 19, P. Wilson describes RF pulse compression in some detail including estimates of efficiencies. An experimental test at SLAC of a low-loss, low-power system has been completed which yielded a factor of 3.2 power gain.[20] Recently, a high-power RF pulse compressor, designed to yield a power gain of 6, has been completed at SLAC. This has been tested at low power and has achieved a gain of 5.5.[21] This will be powered with a high-power 11.4 GHz klystron designed to yield 100 MW peak power. The second prototype of this klystron has achieved 75 MW in short pulses and 50 MW in long pulses.

Recently, a new method of RF pulse compression has been developed at SLAC.[22] This technique, dubbed SLED II, is similar in spirit to the SLED RF pulse compression system which is presently used to provide RF pulse compression for the SLC. In the SLED II method of RF pulse compression, the two high-Q resonators used in the usual SLED system are replaced by two lengths of shorted low-loss transmission line having a round trip delay time equal to the output pulse length. A resonant buildup of energy stored in the lines takes place during an input pulse length which is an integral number of delay periods (typically 4–8). A phase reversal of the input pulse effectively releases the stored energy to produce a flat-top output pulse during the final delay period. Measurements from a low power single-stage SLED II system with a power gain of four have shown excellent agreement with theory.

The design of overmoded low-loss components for a high power SLED II system is presently underway at SLAC. The key feature of SLED II is that it provides substantial pulse compression for nearly an order of magnitude less delay line due to the reflective nature of the scheme.

<u>Magnetic pulse compression and the relativistic klystron</u>: In this case, the pulse compression happens *before* the creation of RF. This technique makes use of the pulsed power work done at LLNL in which magnetic compressors are used to drive induction linacs to produce multi-MeV e^- beams with kiloampere currents for pulses of about 50 nsec. The object, then, is to bunch the beam at the RF frequency and then to extract a significant fraction of this power. This can be done either by velocity modulation or by dispersive magnetic "chicanes." After bunching, the beam is passed by an RF extraction cavity, which extracts RF power from the beam.

Experiments on the relativistic klystron are described in Ref. 23. The best power output achieved to date is 330 MW.[24] Although higher acceleration gradients have been achieved, the best breakdown-free acceleration gradient in this experiment is 84 MV/m with 80 MW of RF power input into a 30 cm long accelerator structure. Due to inefficiency and high cost, this method is presently not thought to be a candidate for an NLC power source.

To conclude this section, if high-power tests of RF pulse compression show positive results, and if the 100 MW klystron achieves its design power, this combination could provide a power source for a Next Linear Collider.

Emittance Preservation

In order to achieve the desired luminosity, we must preserve the emittance of the beam during acceleration. Much experience is being gained at SLC, where BNS[25] damping has been successfully tested and is routinely used in normal operation.[26] For the NLC as conceived at SLAC, chromatic dilution of the bunch has limited tolerances to about 10–20 μm for vertical misalignments. Recently, a new trajectory correction technique, which eliminates the chromatic dilution, has been invented which increases the tolerances on misalignments to values greater than 200 μm rms.[27,28] This technique can be modified when wakefields are included to also provide local cancellation of wakefield effects.[29] Using this new correction technique together with BNS damping and careful structure alignment, we hope to control the emittance growth during acceleration.

FINAL FOCUS

The final focus is designed to produce a flat beam which crosses at a small angle to the oncoming beam. The purpose of the flat beam is to increase the luminosity while controlling beamstrahlung and disruption. The crossing angle is to allow different size apertures for the incoming and outgoing beam. Another invention, "crab-wise crossing", discussed in Ref. 30, allows a much larger crossing angle than the diagonal angle of the bunch. This technique can be used to a greater or lesser extent depending upon backgrounds at the collision point.

Final Focus Optics and Tolerances

The small spot size necessary to obtain the luminosity shown in Table 1 is obtained by the combination of a small emittance beam with a large optical demagnification. The job of the final focus is to produce this large demagnification. Much progress has been made on the optical design of final focus systems which can achieve the necessary spot sizes.[31,32,33] The limiting effect seems to be the radiation of the particles in the final quadrupoles which yields a minimum vertical spot size in the nanometer range.[34]

Once the design is specified, one is led to the question of the sensitivity of the design to different types of errors. The most serious vibration tolerance is in the final doublet, but there seem to be solutions to provide the required isolation.[35]

Alignment tolerances in the absence of any correction are quite tight; it has, however, been recently shown that one can recover from misalignments in the range 10–30 μm.[36] There is much more work to be done here, but the initial results indicate that tuning will be possible in the presence of errors.

Final Focus Test Beam

A Final Focus Test Beam (FFTB) is being constructed at SLAC in order to test the optical demagnification necessary for an NLC and to address the technical issues relevant to an actual NLC final focus.[37] The FFTB is presently supported by a collaborative effort of SLAC, INP, KEK, Orsay and DESY. The beam line, shown in Fig. 2, consists of a chromatically-corrected final focus with a non-interlaced

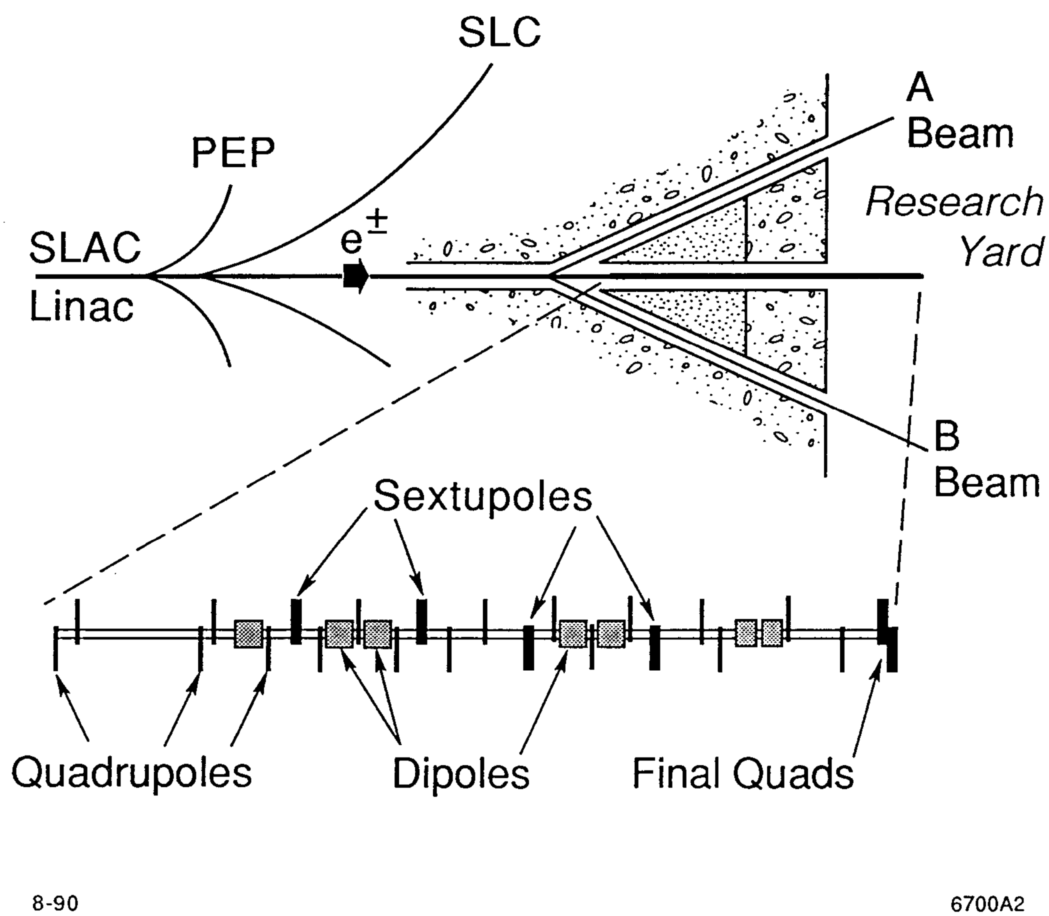

Fig. 2. Final Focus Test Beam.

sextupole correction. The goal is to produce a flat beam which is 60 nm high by 1 μm wide. The detailed design is complete and construction has begun.

SUMMARY

Research at SLAC is focused on the two key parameters of a Next Linear Collider, the energy and luminosity. On the energy side, we have demonstrated damped structures, RF pulse compression, and have tested initial prototypes of high-power klystrons. On the luminosity side, we have designed damping rings and bunch compressors and have studied preservation of emittance, both theoretically and experimentally. New studies bring the magnet alignment tolerances for the linac into the range greater than 100 μm. The Final Focus Test Beam is being constructed and will test the optical demagnification necessary for an NLC. We look forward to a design in the early to mid-1990's.

REFERENCES

1. Proceedings of the Workshop on Physics of Linear Colliders, Capri, Italy (1988).
2. Proc. of the Summer Study on High Energy Physics in the 1990's, Snowmass, Colorado, July 1988, World Scientific, Singapore (1989).
3. Proceedings of the International Workshop on Next Generation Linear Colliders, SLAC, Stanford, CA, Dec. 1988, SLAC-Report-335.
4. Linear Collider Working Group Reports From Snowmass '88, Ed. R. D. Ruth, SLAC-Report-334.
5. Proceedings of the 1990 Workshop on Next Generation Linear Colliders, KEK, Tsukuba, Japan, March 1990.
6. Raubenheimer, T.O., Rivkin, L.Z. and Ruth, R.D. "Damping Ring Designs for a TeV Linear Collider'" SLAC–PUB–4808 (1988) and in Refs. 2 and 4.
7. Raubenheimer, T.O. *et al.*, "A Damping Ring Design for Future Linear Colliders," Proc. of 1989 IEEE Part. Acc. Conf., Chicago, Ill., p. 1316, and in SLAC–PUB–4912.
8. Kheifets, S.A., Ruth, R.D., Murray, J.J. and Fieguth, T.H., "Bunch Compression for the TLC. Preliminary Design," SLAC–PUB–4802 (1988), and in Refs. 2 and 4.
9. Kheifets, S.A., Ruth, R.D. and Fieguth, T.H., "Bunch Compression for the TLC," Proc. of Int. Conf. on High Energy Acc., Tsukuba, Japan (1989) and in SLAC–PUB–5034.

10. Loew, G.A. and Wang, J.W., "RF Breakdown Studies in Room Temperature Electron Linac Structures," SLAC–PUB–4647 (1988), and in Refs. 2 and 4.
11. Loew, G.A. and Wang, J.W., "Field Emission and RF Breakdown in Copper Linac Structures," Proc. of the 14th Int. Conf. on High Energy Acc., Tsukuba, Japan (1989), and in SLAC–PUB–5059.
12. Ruth, R.D., "Multibunch Energy Compensation," SLAC–PUB–4541 (1989), and in Ref. 1.
13. Thompson, K.A. and Ruth, R.D., "Controlling Transverse Multibunch Instabilities in Linacs of High Energy Linear Colliders," Phys. Rev. D, 41, p. 964 (1990), and in SLAC–PUB–4801 (1989)
14. Thompson, K.A. and Ruth, R.D., "Multibunch Instabilities in Subsystems of 0.5 and 1.0 TeV Linear Colliders," SLAC–PUB–4800 (1988), and in Refs. 2 and 4.
15. Palmer, R.B., "Damped Accelerator Cavities," SLAC–PUB–4542 (1988), and in Refs. 2 and 4.
16. Deruyter, H. *et al.*, "Damped Accelerator Structures," Proc. of the 2nd European Part. Acc. Conf., Nice, France, (1990), and in SLAC–PUB–5263.
17. Kroll, N.M. and Yu, D.U.L., "Computer Determination of the External Q and Resonant Frequency of Waveguide Loaded Cavities," Particle Accel., 34, 231 (1990), and in SLAC–PUB–5171.
18. Farkas, Z.D., "Binary Peak Power Multiplier and its Application to Linear Accelerator Design," IEEE Transcripts on Microwave Theory and Techniques, MTT–34, No. 10, p. 1036 (1986), and SLAC–PUB–3694.
19. Wilson, P.B., "RF Pulse Compression and Alternative RF Sources," SLAC–PUB–4803 (1988), and in Refs. 2 and 4.
20. Farkas, Z.D., Spalek, G. and Wilson, P.B., "RF Pulse Compression Experiment at SLAC," Proc. of 1989 IEEE Part. Acc. Conf., Chicago, Ill. (1989), and in SLAC–PUB–4911.
21. Lavine, T.L. *et al.*, "Binary RF Pulse Compression Experiment at SLAC," Proc. of the 2nd European Part. Acc. Conf., Nice, France (1990), and in SLAC–PUB–5277.
22. Wilson, P.B., Farkas, Z.D. and Ruth, R.D., "SLED-II: A New Method of RF Pulse Compression," Proc. of Linear Accelerator Conf., Albuquerque, NM (1990), and in SLAC–PUB–5330.
23. Allen, M.A. *et al.*, "High Gradient Electron Accelerator Powered by a Relativistic Klystron," Phys. Rev. Lett. 63, p. 2472 (1989).
24. Allen, M.A. *et al.*, "RF Power Sources for Linear Colliders," Proc. of 2nd European Part. Acc. Conf., Nice, France (1990), and in SLAC–PUB–5274.

25. Balakin, V., Novokhatsky, A. and Smirnov, V., Proc. of the 12th Int. Conf. on High Energy Accelerators, Fermilab, p. 119 (1983).

26. Seeman, J., SLAC–PUB–4968 (1990), to be published.

27. Raubenheimer, T.O. and Ruth, R.D., "A New Trajectory Correction Technique for Linacs," Proc. of the 2nd European Part. Acc. Conf., Nice, France (1990), and in SLAC–PUB–5279.

28. Raubenheimer, T.O. and Ruth, R.D., "A Dispersion-Free Trajectory Correction Technique for Linear Colliders," SLAC–PUB–5222 (1990), submitted for publication.

29. Raubenheimer, T.O., "A New Technique for Correcting Emittance Dilutions in Linear Accelerators," SLAC–PUB–5355 (1990).

30. Palmer, R.B., "Energy Scaling, Crab Crossing and the Pair Problem," SLAC–PUB–4707 (1988), and in Refs. 2 and 4.

31. Oide, K., "Final Focus System for TLC," SLAC–PUB–4806 (1988), and in Refs. 2 and 4.

32. Irwin, J., "The Applications of Lie Algebra Techniques to Beam Transport Design," to be published in Nucl. Inst. & Meth., and in SLAC–PUB–5315 (1990).

33. Murray, J.J., Brown, K.L. and Fieguth, T.H., "The Completed Design of the SLC Final Focus System," Washington PAC 1987:1331, and SLAC–PUB–4219 (1987).

34. Oide, K., "Synchrotron Radiation Limit on the Focusing of Electron Beams," Phys. Rev. Lett., 61, 1713 (1988).

35. Ash, W.W., "Final Focus Supports for a TeV Linear Collider," SLAC–PUB–4782 (1988), and in Refs. 2 and 4.

36. Irwin, J. and Oide, K., private communication.

37. Buon, J., "Final Focus Test Beam for the Next Linear Collider," Proc. of the 2nd European Part. Acc. Conf., Nice, France, 1990.