SLAC-PUB-5283
June 1990
(A)

RESEARCH AT SLAC TOWARDS A 0.5 TeV LINEAR-COLLIDER*

RONALD D. RUTH
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309

1. INTRODUCTION

The purpose of this paper is to review the ongoing research at SLAC towards 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 TeV. The luminosity is in the range of 10^{33} to 10^{34} $\text{cm}^{-2}\,\text{sec}^{-1}$. 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 will be based on total cost. A very broad optimum occurs when the total linear costs equal the total cost of RF power.

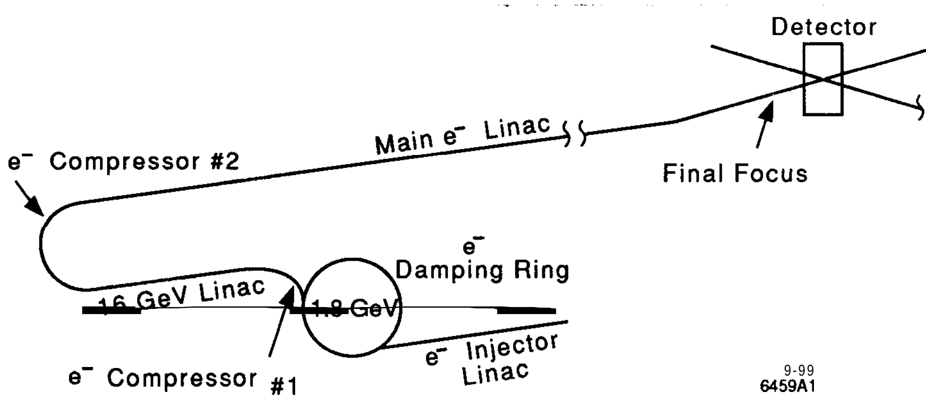

Figure 1. Schematic of a Next Linear Collider.

Invited talk presented at the 15th APS Division of Particles and Fields General Meeting, Houston, TX, January 3-6, 1990.

⋆ Work supported by Department of Energy contract DE–AC03–76SF00515.

The luminosity of the linear collider is obtained primarily in two ways. First, the cross-sectional area of the beam 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 and brief table of important parameters are shown in Fig. 1 and Table 1, respectively. 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.

Table 1. Parameters for a 0.5 TeV NLC.

Parameter	Value
CM energy	0.5 TeV
Luminosity 10^{33}	3.9 cm^{-2} sec^{-1}
RF frequency	11.4 GHz
Repetition rate	360.0 Hz
Acceleration gradient	93.0 MV/m
Number of bunches	10
Particles/bunch (at IP)	1.6×10^{10}
Length	7.2 Km
β_y^*	0.08 mm
Crossing angle (no crab)	4.8 mrad
Crab crossing angle	30-100 mrad
σ_y	3.1 nm
σ_x/σ_y	180
σ_z	70.0 μm
Disruption D_y	10.0
Luminosity enhancement H	1.5
Beamstrahlung δ	6%

2. DAMPING RINGS

In Refs. 6 and 7, T. Raubenheimer *et al.* discuss many of the basic design considerations for the damping ring. The basic parameters are shown in Table 2 where they are compared to those of the SLC. The key differences are the decrease of the horizontal emittance by an order of magnitude, the increase of the repetition rate, and the requirement of ϵ_x/ϵ_y = 100. Although asymmetrical emittances have been measured in the SLC damping ring, they are not required for SLC operation.

The desired repetition rate is obtained by having many batches of bunches in the ring. Each batch of 10 bunches is extracted on one kicker pulse and accelerated on one RF fill in the linac. The remaining batches are left in the ring to continue damping, while an additional batch is injected to replace the extracted one.

The basic layout of a possible damping ring is shown in Fig. 2. Notice that there are several insertions which contain wigglers. In order to obtain the high repetition rate, it may be necessary to decrease the damping time by the addition of wigglers in straight sections. However, if the desired repetition rate is decreased by a factor of two, it is probably not necessary to include wigglers to decrease the damping time.

Table 2. Basic parameters of NLC and SLC damping rings.

	NLC	SLC
Energy, E_0	1.8 GeV	1.15 Gev
Length, L	155.1 m	35.3 m
RF frequency, f_{RF}	1.4 GHz	714 MHz
Repetition rate	360 Hz	120 Hz
Emittance, $\gamma\epsilon_x$	3.0 μmrad	36 μmrad
Emittance, $\gamma\epsilon_y$	30 nmrad	500 nmrad
Damping time, τ_x	2.50 ms	3.4 ms
Damping time, τ_y	3.98 ms	3.4 ms
Energy spread, σ_ϵ	0.0010	0.0007
Bunch length, σ_z	5.2 mm	5 mm[8]
Vertical size	3 μm	20 μm
Horizontal size	30 μm	100 μm

3. BUNCH COMPRESSION AND PRE-ACCELERATION

In order to obtain the very short bunches necessary for the linac, it is necessary to perform at least two bunch compressions after the damping ring. Designs for such bunch compression are presented in Refs. 9 and 10. A bunch length of about 50 μm in the linac puts a constraint on the longitudinal emittance of the damping ring. In addition, during the bunch compressions, it is necessary to keep the energy spread small to avoid the dilution of the transverse emittance. If we assume that we can transport 1% energy spread without diluting either transverse emittance, then at least two bunch compressions are needed. For example, if we consider a 1.8 GeV damping ring with an energy spread of $\Delta E/E = 10^{-3}$ and a bunch length of 5 mm, the two compressions are shown in Table 3. The first one decreases the bunch length

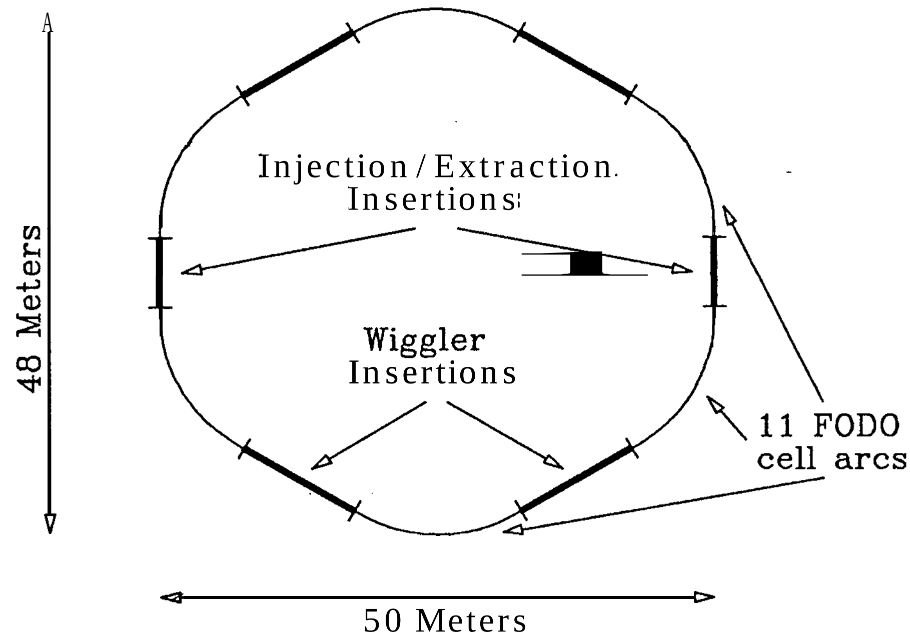

Figure 2. Schematic of an NLC damping ring.

by an order of magnitude. This is followed by a pre-acceleration section to decrease the relative energy spread in-the beam by about an order of magnitude. One must avoid an increase of energy spread due to the cosine of the RF wave (and also due to beam loading). If this pre-acceleration is done at the present SLAC frequency and if the bunch intensity is in the range l-2 x 10^{10}, then the additional energy spread induced is quite small. Neglecting this small increase, the next bunch compression happens around 18 GeV and serves to reduce the bunch length to about 50 μm. This is suitable for injection into the high frequency, high gradient structure.

Table 3. Bunch compression.

E	$\Delta E/E$	σ_z	Compress $\rightarrow$	$\Delta E/E$	σ_z
1.8 GeV	10^{-3}	5 mm	Compress $\rightarrow$	10^{-2}	0.5 mm
[pre-acceleration at long wavelength, λ = 10.5 cm]					
18 GeV	10^{-3}	0.5 mm	Compress $\rightarrow$	10^{-2}	50 μm

Reference 10 presents several designs in which the bend angle for the final compressor is 180° as shown in Fig. 1. This low-energy bend allows easy upgrades in energy, and also makes it possible to do direct feedback to compensate jitter from the damping ring kicker magnet.

4. 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 may have other modifications to damp long-range transverse wakefields. This would be driven by a power source capable of about 220 MW/m in order to obtain an accelerating field of 100 MV/m.

The remainder of this section is divided into two subsections. In the first subsection we discuss structures, while the second deals with RF power sources.

4.1; -Structures

Since the acceleration gradients being considered range from 100 MV/m to 200 MV/m, the first question that arises is RF breakdown. This question is treated in Refs. 11 and 12. In these papers, G. Loew and J. Wang present results from many experiments at various frequencies. If the scaling laws thus obtained are extrapolated to 11.4, 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 needs further study.

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: (1) the energy of the bunches in the train must be controlled and (2) the transverse stability of the bunch train must be ensured. Both of these problems are helped greatly by damping higher modes (both transverse and longitudinal) in the RF structure. In Ref. 13, R. Palmer describes a technique of using slotted irises coupled to radial waveguides to damp these modes: Q's as low as 10–20 have been measured in model structures. This encouraging evidence has led to a development program at SLAC and KEK 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.[14,15] The beam dynamics consequences of damping the higher modes are explored in Section 6.

4.2. 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.

42.1. RF Pulse Compression and *Conventional Klystrons*

In Fig. 3(a), you see illustrated the basic principle of RF pulse compression. A long modulator pulse is converted by a high-power, "semiconventional" klystron or

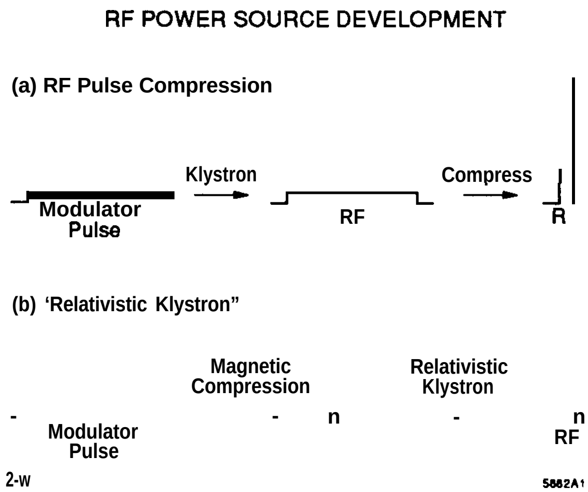

Figure 3. (a) Illustration of RF pulse compression; and (b) illustration of the relativistic klystron with magnetic compression.

some other power source into RF power with the same pulse width. This RF pulse is then compressed by slicing the pulse using phase shifts and 3 db hybrids and rerouting 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.[16] 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 100 MV/m.

In Ref. 17, 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.[18] 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.[19] This will be powered with a high-power 11.4 GHz klystron designed to yield 100 MW peak power. An initial prototype of this klystron has achieved 65 MW in short pulses and 25 MW in long pulses.[20]

4.2.2. Magnetic *Pulse* Compression and the Relativistic *Klystron*

In Fig. 3(b), you see the principle of magnetic pulse compression and the relativistic klystron illustrated. 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. These e^- beams contain gigawatts of power. 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. 21. The best power output achieved to date is 330 MW.[20] 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.

4.2.3. Other RF Sources

It is also possible to consider other sources driven by magnetic pulse compressors which directly produce short, high-power RF pulses. One example is a cross-field amplifier (CFA). This device has the geometry of a magnitron but is configured as an amplifier rather than an oscillator. SLAC has completed the construction of a CFA designed to produce 100 MW. This initial prototype has achieved about 10 MW peak output power. Although it is a large extrapolation from existing sources, it holds the promise of being less expensive than an equivalent power klystron.

Another interesting possible RF source is the cluster klystron. In Ref. 22, R. Palmer and R. Miller describe a multiple beam array of "klystrinos" which when coupled together can give impressive results. By dividing a single beam into many beams shielded from each other, the problems of space charge are effectively eliminated. This source could be used as a driver for RF pulse compression. Alternatively, with the addition of a grid and an oil-filled transmission line for energy storage, the device could directly produce short RF pulses. Thus far, there has been no experimentation, but calculations and cost estimates are encouraging.

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.

5. FINAL FOCUS

The final focus, as described in the parameters in Table 1, is a flat beam final focus with a crossing angle. 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. 23, allows a much larger crossing angle than the diagonal angle of the bunch. As discussed in Ref. 23 and in Ref. 24, this type of geometry may now be essential due to the production of e^+e^- pairs by beamstrahlung photons in the field of the bunches.

5.1. Final Focus Optics and Tolerances

The first job in the final focus is to demagnify the beam to provide a small spot for collision. A design for such a system is presented in Ref. 25 by K. Oide. This is a flat beam final focus which achieves the parameters shown in Table 1 for vertical and horizontal beam size. The vertical size is limited by a fundamental constraint, the "Oide limit," due to the synchrotron radiation in the final doublet coupled to the chromatic effect of a quadrupole. The quadrupole gradients necessary are very high, and in Oide's design are obtained by conventional iron magnets with 1 mm pole-to-pole distance. Tolerances are very tight in such a final focus. The most restrictive vibration tolerance is on the final doublet which must be stable pulse-to-pulse to about 1 nm.

Since vibration of the final doublet is the most serious problem, it is considered in some detail in Ref. 26. In this paper, it is shown that passive vibration isolation seems to be more than adequate to handle the vibrations above 10 Hz at the high frequency end. For low frequencies, an interferometric feedback system can be used to control motion down to about 1 μm. Beam steering feedback can then be used to control slow variations in the 1 nm to 1 μm region.

5.2. Beam-Beam Effects

When a small bunch of electrons collides with a small bunch of positrons, the fields of one bunch focus the other causing disruption. Since the opposing particles are strongly bent, they also emit radiation called beamstrahlung. These are the two basic beam-beam effects. The disruption enhances the luminosity by a small amount, while the beamstrahlung causes significant energy loss during collision and increases the effective momentum spread for physics. These issues are discussed in detail in Ref. 24.

In addition, there are several other important effects which should be mentioned here. If the beams are offset relative to each other, a kink instability develops. For small disruption, this effect actually causes the luminosity to be less sensitive to offsets because the beams attract each other and collide anyway. There is also a multibunch kink instability, which is more serious since it can cause the trailing bunches to miss each other entirely. This places restrictions on the product of the vertical and horizontal disruption per bunch.

As mentioned earlier in the Introduction, it has been discovered that beamstrahlung photons pair-produce in the coherent field of the bunch.[27–30] The corresponding incoherent process has been known for some time, but its importance has only just been realized.[31] The problem is that low-energy e^+e^- pairs are produced in an extremely strong field, which then deflects the charge of the appropriate sign while confining the other.

These stray particles can lead to background problems, which must be addressed by detailed interaction point design. In Ref. 23, it is suggested that crab-crossing combined with large crossing angles and solenoidal fields would allow one to channel these electrons out through a large exit hole to a beam dump. Further studies of this option have indicated that crossing angles in the range 30-100 mrad would be necessary to avoid particle impact in the detector.[32]

The measurement of the final spot size is an extremely important, but as yet unsolved, problem. From SLC experience, it is probably possible to use beam-beam effects to minimize spot sizes. However, for the initial tune-up of-the final focus, a single-beam method is almost essential. Initial studies of this problem use the energy and angular distribution of ions from a gas jet which is intercepted by the beam.[33] However, there is clearly much more work needed in this area.

6. MULTIBUNCH EFFECTS

As mentioned earlier, in order to efficiently extract energy from the RF to obtain high luminosity, it is essential to have many bunches per RF fill. This, however, leads to transverse beam breakup. The invention of damped structures discussed in Section 5.1 helps but may not completely solve the problem for the linac. It may also be necessary to tune the frequency of the first dipole mode of the accelerating structure.[34] In Ref. 35 the problem of multibunching is traced all the way through the linear collider, subsystem by subsystem. Damped accelerating cavities are required for the main linac and the damping rings, while other systems can get by with very strong focusing. Thus, from the transverse point of view, stability seems possible.

In addition, it is necessary to control the energy spread from bunch to bunch very precisely ($\Delta E/E \lesssim 10^{-3}$). This can be accomplished by injecting the bunches before the RF structure is full to match the extraction of energy by the bunches to the incoming energy as the structure fills. This leads to tight tolerances on phase and amplitude of the RF, as well as tight control of the pulse-to-pulse number of particles in a batch of bunches. [36] However, the benefits of multibunching seem to far outweigh any difficulties they impose due to the order of magnitude increase in luminosity.

7. OUTLOOK

During the past few years, there has been tremendous progress towards a next-generation linear collider. We now have a much clearer picture of how to obtain both the energy and luminosity required. An important development is the increased interest in a linear collider with 0.5 TeV in the CM which would be upgradable to 1.0 TeV with additional power sources or length. We will probably see the development of a power source and structure during the next couple of years. This would yield the energy of the collider; what about the luminosity?

Designs of damping rings, bunch compressors and final focus systems will continue. Studies of BNS damping in the linac and emittance dilution will continue both experimentally with the SLC and theoretically for the next-generation high-frequency linac. However, to really understand tolerances, new measurement techniques, and final focus optics, it is probably essential to build a scale model final focus at SLC energy. This is being planned at SLAC (Final Focus Test Beam) and is being supported as a collaborative effort of SLAC, INP, KEK, Orsay, and DESY.

One key aspect of all linear collider design is background control. This problem is complicated by pair production during the bunch crossing; however, detailed studies of interaction point design are underway at SLAC, KEK, and INP.

To conclude, it looks like we are on the path towards a next-generation linear collider, and with proper funding of R&D over the next few years we may see a detailed conceptual design in the mid-1990s.

REFERENCES

1. *Proc.* ***Workshop on Physics of Linear Colliders,*** Capri, Italy, June 1988.
2. *Proc.* ***Summer Study on High Energy Physics*** in ***the 1990's,*** Snowmass, Colorado, July 1988 (World Scientific, Singapore, 1989).
3. *Proc.* ***Int. Workshop on Next-Generation Linear Colliders,*** SLAC, Stanford, CA, December 1988; SLAC-Report-335.
4. ***Linear Collider Working Group Reports From Snowmass*** 88, Ed. R. D. Ruth, SLAC-Report-334.
5. *Proc.* ***1990 Workshop on Next-Generation Linear Colliders,*** KEK, Tsukuba, Japan, March 1990.
6. T. 0. Raubenheimer, L. Z. Rivkin, and R. D. Ruth, "Damping Ring Designs for a TeV Linear Collider," SLAC-PUB-4808 (1988); and in Refs. 2 and 4.
7. T. 0. Raubenheimer ***et al.,*** "A Damping Ring Design for Future Linear Colliders," *Proc.* ***1989 IEEE Part. Acc. Conf.,*** p. 1316; SLAC-PUB-4912 (1989).
8. L. Z. Rivkin ***et al.,*** "Bunch Lengthening in the SLC Damping Ring," SLAC–PUB-4645 (1988).
9. S. A. Kheifets, R. D. Ruth, J. J. Murray, and T. H. Fieguth, "Bunch Compression for the TLC. Preliminary Design," SLAC-PUB-4802 (1988); and in Refs. 2 and 4.
10. S. A. Kheifets, R. D. Ruth, and T. H. Fieguth, "Bunch Compression for the TLC," *Proc.* ***Int. Conf. on High Energy Part. Acc.,*** Tsukuba, Japan, 1989; SLAC-PUB-5034 (1989).
11. G. A. Loew and J. W. Wang, "RF Breakdown Studies in Room Temperature Electron Linac Structures," SLAC-PUB-4647 (1988); and in Refs. 2 and 4.
12. G. A. Loew and J. W. Wang, "Field Emission and RF Breakdown in Copper Linac Structures," *Proc.* ***14th Int. Conf. on High Energy Part. Acc.,*** Tsukuba, Japan, 1989; SLAC-PUB-5059.

13. R. B. Palmer, "Damped Accelerator Cavities," SLAC-PUB-4542 (1988); and in Refs. 2 and 4.

14. H. Deruyter ***et al.,*** "Damped Accelerator Structures," *Proc. 2nd* ***European Part.*** *Acc.* ***Conf.,*** June, 1990.

15. N. M. Kroll and D. U. L. Yu, "Computer Determination of the External Q and Resonant Frequency of Waveguide Loaded Cavities," SLAC-PUB-5171, to be published.

16. Z. D. Farkas, "Binary Peak Power Multiplier and Its Application to Linear Accelerator Design," ***IEEE Transcripts on Microwave Theory and Techniques,*** **MTT–34,** No. 10, 1036 (1986); SLAC-PUB-3694.

17. P. B. Wilson, "RF Pulse Compression and Alternative RF Sources," SLAC–PUB-4803 (1988); and in Refs. 2 and 4.

18. Z. D. Farkas, G. Spalek, and P. B. Wilson, "RF Pulse Compression Experiment at SLAC," *Proc.* ***IEEE Part.*** *Acc.* ***Conf.,*** 1989; SLAC-PUB-4911 (1989).

19. T. L. Lavine ***et al.,*** "Binary RF Pulse Compression Experiment at SLAC," *Proc. 2nd* ***European Part.*** *Acc. Conf.,* June 1990; SLAC-PUB-5277.

20. M. A. Allen ***et al.,*** "RF Power Sources for Linear Colliders," *Proc. 2nd* ***European Part.*** *Acc.* ***Conf.,*** June 1990; SLAC-PUB-5274.

21. M. A. Allen ***et al.,*** "High Gradient Electron Accelerator Powered by a Relativistic Klystron," ***Phys. Rev. Lett. 63,*** 2472 (1989).

22. R. B. Palmer and R. Miller, "A Cluster Klystron," SLAC-PUB-4706 (1988); and in Refs. 2 and 4.

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

24. P. Chen, "Disruption, Beamstrahlung, and Beamstrahlung Pair Creation," SLAC-PUB-4822 (1988); and in Refs. 2 and 4.

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

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

27. R. Blankenbecler, S. D. Drell, and N. Kroll, "Pair Production From Photon Pulse Collisions," ***Phys. Rev.*** D40, 2462 (1989); SLAC-PUB-4954.

28. P. Chen and V. I. Telnov, "Coherent Pair Creation in Linear Colliders," ***Phys. Rev. Lett.*** 63, 1796 (1989); SLAC-PUB-4923.

29. M. Jacob and T. T. Wu, "Pair Production in Bunch Crossing," ***Phys. Lett.*** **B221, 203** (1989).

30. V. N. Baier, V. M. Katkov, and V. M. Strakhovenko, *Proc. 14th Int. Conf.* on High Energy Part. *Acc.,* Tsukuba, Japan, 1989.

31. M. S. Zolotarev, E. A. Kuraev, and V. G. Serbo, "Estimates of Electromagnetic Background Processes for the VLEPP Project," Inst. Yadernoi Fiziki, Preprint 81-63 (1981); English Translation SLAC TRANS-0227 (1987).

32. J. Irwin, private communication.

33. J. Buon, *Proc. 14th Int. Conf.* on **High** Energy Part. *Acc.,* Tsukuba, Japan, 1989.

34. K. A. Thompson and R. D. Ruth, "Controlling Transverse Multibunch Instabilities in Linacs of High Energy Linear Colliders," *Phys.* ***Rev.*** **D41, 964** (1990); SLAC-PUB-4801 (1989).

35. K. A. Thompson and R. D. Ruth, "Multibunch Instabilities in Subsystems of 0.5 and 1.0 TeV Linear Colliders," SLAC-PUB-4800 (1988); and in Refs. 2 and 4.

36. R. D. Ruth, "Multibunch Energy Compensation," SLAC-PUB-4541 (1989); and in Ref. 1.