SLAC R&D TOWARD A TEV LINEAR COLLIDER*

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INTRODUCTION

At CERN, KEK, Novosibirsk and SLAC, serious thought is being given to the design of linear colliders in the 0.5–2.0 TeV center-of-mass energy range. This paper reviews current progress at SLAC toward the design of such a collider. No attempt is made here to summarize ongoing work at the other laboratories. However, research on linear colliders is clearly an international effort, and success at SLAC will be greatly expedited by communication and cooperation with other laboratories in the U.S. and abroad. In addition to major programs at the laboratories mentioned above, contributions relevant to linear collider design are being made at DESY, LAL (Orsay), LBL, LLNL and elsewhere.

In late 1986, SLAC director Burton Richter convened two committees to look at particle physics and accelerator technology issues for a future linear collider with a center-of-mass energy in the range 0.5–1.0 TeV. The lower bound represents a reasonable minimum next step in energy beyond LEP II. The upper bound represents a guess for a maximum reasonable step from the SLC to a future collider. It is also an energy that can be reached by a machine that would fit on a Stanford site, if an energy gradient on the order of 180 MeV/m can be achieved.

The work of the physics committee, chaired by M. E. Peskin, has been completed; the conclusions are presented in Ref. 1. Although the committee did not find an iron-clad argument that 1 TeV center-of-mass would necessarily suffice to uncover the next scale of physics, they did 'find compelling the idea that the decade or so in energy above 100 GeV contains a new sector of physical forces waiting to be discovered.'[1] Concerning luminosity, the committee concluded that at 1 TeV it should be 'in excess of 10^{33} cm^{-2} sec^{-1}.' A fractional beamstrahlung energy loss of $\delta = 0.26$ was found to be acceptable. It was found, in fact, that the beamstrahlung loss is not a particularly sensitive parameter. The committee concluded that it is of central importance to obtain the highest possible luminosity, and that luminosity should not be traded away to reduce the beamstrahlung loss.

The accelerator committee, chaired by J. M. Paterson, has not issued a formal report because the work is still in progress. More precisely, it is just beginning at a serious level. Several years of work at this level will be required to produce a detailed design for a TeV collider. In addition to theoretical work, prototypes for a number of systems or components must be built and tested. In order to produce a credible design, an rf source must be demonstrated which is acceptable on the basis of both performance and cost. Prototypes must also be tested for the high gradient accelerating structure, for the elements of a final focus system for submicron sized beams, and for beam diagnostic instrumentation. The R&D program is planned and coordinated by the Accelerator Theory and Special Projects Department at SLAC, led by J. M. Paterson. The goal of this program is to produce a detailed design proposal for a TeV Linear Collider (TLC) by the early 1990's.

PARAMETERS

It has been often noted that the parameters for a linear collider are interrelated by a complex web of theoretical and practical constraints. Palmer[2] has emphasized this interdependence of collider parameters, and has put the design relationships and known constraints into analytic form. A computer program[3] then solves these expressions to obtain a consistent set of collider parameters. It is important to note that these design expressions are in many cases only approximate. Detailed design studies must still be carried out for each major subsystem, for example the damping ring and final focus. Nevertheless, the results of this program at least direct us to the right neighborhood in a highly complex parameter space, and also are helpful in determining the scaling of output parameters for perturbations in the input data.

The principle interaction point (IP) parameters for a recent[4] TLC design are given in Table I. Details of the expressions used and any approximations made are discussed in Ref. 2. Note that this design assumes flat beams with an aspect ratio of $R = 134$ crossing at an angle $\theta_c = 3.9 \times 10^{-3}$. The luminosity is reduced in this case by a factor of 0.78 below that for head-on collisions. As desired by the Physics Committee, the luminosity is indeed 'in excess of 10^{33} cm^{-2} sec^{-1}.' By designing for a higher luminosity, the hope is that 10^{-33} cm^{-2} sec^{-1} can be reached in a reasonable time after turn-on with the capability to approach the design luminosity with time. In addition, Palmer's design program now includes several "dilution factors," which take into account the possibility of transverse emittance growth in the main linac, particle loss between the damping ring and final focus, degradation in the betas of the final-focus optics, and longitudinal emittance growth due to bunch lengthening in the damping ring and to phase-space distortions during bunch compression. The dilution factors are listed in Table II. Note that the undiluted luminosity would be nearly 3×10^{34} cm^{-2} sec^{-1}.

The design in Table II is based on an accelerating gradient of 186 MV/m. For this gradient, the corrected linac length (both linacs) would need to be only 5.4 km to reach 1 TeV. However, a number of factors serve to increase this length. First, space must be added for the focusing quadrupoles. Allowing 5% for this purpose gives a length factor $f = 1.05$. Second, the bunches run 6.6° off crest in this design ($f = 1.01$). Third, the energy spread needed for BNS damping must be removed by an additional length of linac in which the bunches run at the zero crossing of the rf ($f = 1.08$). And finally, to compensate for the beam loading between the head and the tail of the multibunch train (each bunch removes 2.5% of the energy stored in the linac structure), an additional length factor $f = 1.15$ is necessary. The total length factor is 1.32, giving a corrected linac length of 7.1 km. To this must be added a final focus system (2×300 m) for an overall machine length of

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

7.7 km. A reasonable layout for a machine of this length, but not much longer, can be made on a Stanford site.

Table I. Principle IP parameters for the TLC.

Center-of-mass Energy (TeV)	1.0
Luminosity (cm^{-2} sec^{-1})	6×10^{33}
Vertical Beam Size σ_y^* (m)	2.9×10^{-9}
Horizontal Beam Size σ_x^* (m)	3.9×10^{-7}
Aspect Ratio R	134
Vertical Beta β_y^* (m)	1.1×10^{-4}
Horizontal Beta β_x^* (m)	2.7×10^{-2}
Particles per Bunch N	1.4×10^{10}
Bunch Length σ_z^* (m)	70×10^{-6}
Crossing Angle σ_c	3.9×10^{-3}
Disruption Parameters D_y, D_x	5.0, 0.04
Disruption Enhancement H_{Dy}, H_{Dx}	1.56, 1.00
Quantum Parameter Υ	0.47
Quantum Reduction Factor H_Υ	0.30
Beamstrahlung Parameter δ	0.11
Number of Bunches N_b	10
Bunch Repetition Rate f_b (Hz)	3600
RF Pulse Repetition Rate f_r (Hz)	360

Table II. Dilution factors for design of Table I.

	Dilution Factor	Luminosity Reduction
Transverse Emittance Growth	2.8	0.60
Final Focus β_y^*, β_x^*	$(1.2)^2$	0.83
Particle Loss, DR to Linac	1/1.2	0.69
Particle Loss, Linac	1/1.2	0.69
Longitudinal Emittance Growth	1.40	0.93
Total luminosity reduction		0.22

The choice of an rf frequency enters into the collider design expressions in a number of important ways.[2] There is no precise analytic solution to the question of the optimum rf frequency. The best that can be done is to calculate consistent designs over a range of frequencies, then check each design for weaknesses and difficulties with respect to tolerance requirements, etc. The most viable design, the design with the fewest minuses, gives the optimum. When this procedure is carried out for a collider with the energy, luminosity, and accelerating gradient proposed here, and imposing also a limit on wall plug power of 200 MW, it is found that 10 GHz seems to be on the low side, 30 GHz definitely on the high side, and the optimum somewhere in between. A wavelength of 1.75 cm (a frequency six times SLAC's) is chosen for the design presented here. Choosing an iris aperture in the accelerating structure which is reasonably large to reduce wakefield effects (again, this represents a "soft" optimization), we obtain the rf parameters listed in Table III.

Table III. RF parameters for TLC.

RF Frequency	17.14 GHz
Iris Hole Radius	3.50 mm
Group Velocity	0.082 c
Attenuation Parameter τ	0.60
Elastance per Meter	1.74×10^{15} ohms/sec/m
Filling Time	60 ns
Length per Feed	1.6 m
Accelerating Gradient	186 MV/m
Peak Surface Field/Accel. gradient	2.5
Pulse Repetition Rate	360 Hz
Peak RF Power/m	586 MW/m
Ave. RF Power/m	12.6 KW/m

The peak power requirement of 586 MW/m (or 937 MW/feed) is going to be very difficult to meet at this rf frequency. The relativistic klystron, to be discussed later, has been suggested as a source that is capable of generating a peak power on the order of several gigawatts at a pulse length equal to the filling time (60 ns) of the accelerating structure. Another possibility is rf pulse compression. Assuming compression by a factor of eight at 85% efficiency, an rf source at 17 GHz is required which produces a peak power of 86 MW/m (or 138 MW/feed) at a pulse length of 480 ns. The active length of structure which must be supplied by rf power is 6.75 km, giving a total of 4220 feeds. The production of the required rf power at a reasonable cost is clearly one of the most difficult technological issues to be resolved.

The difficulty and cost of producing rf power for the TLC has led to the concept of an ILC (Intermediate Linear Collider). For the ILC, the length is kept the same, but the energy is reduced to 0.5 TeV center-of-mass and the accelerating gradient to 93 MV/m. The number of rf sources, or the peak power per source, can be reduced by a factor of four. It is probable that the ILC is also closer to an optimum design based on an equalization of the power related and length related costs. The IP parameters for the ILC are given in Table IV.

In the following sections a brief overview is given of the ongoing R&D at SLAC on the various collider subsystems. An attempt is made to give a fairly complete list of references to work recently published or soon to be published. The reader is referred to these references for details.

DAMPING RINGS

Table V give some parameters for a damping ring design calculated by Raubenheimer et al.[5] This design combines FODO cells with six insertions. Four insertions are used for wigglers with a total length of 22 m. The ring contains ten batches of ten bunches each. One batch is kicked out every 1/360 second, after seven damping times in the ring. It is calculated[6,7] that the coupling can be reduced to give an emittance ratio $\epsilon_{nx}/\epsilon_{ny} \approx 100$.

Bunch lengthening imposes a severe limit on the allowable impedance for a damping ring. Bunch lengthening has been measured[8] and the longitudinal impedance calculated[9,10] for the present SLC damping ring. The Z/n at low frequencies is $\approx$ 2–3 ohms for the SLC ring. This must be reduced by an order of magnitude to meet the requirements of the design in Table V. Multibunch instabilities in the damping ring have also been considered.[11]

Table IV. Principle IP parameters for the ILC.

Center-of-mass Energy (TeV)	0.5
Luminosity (cm^{-2} sec^{-1})	1.1×10^{33}
Vertical Beam Size σ_y^* (m)	3.0×10^{-9}
Horizontal Beam Size σ_x^* (m)	4.4×10^{-7}
Aspect Ratio R	149
Vertical Beta β_y^* (m)	8.1×10^{-5}
Horizontal Beta β_x^* (m)	2.2×10^{-2}
Particles per Bunch N	6.9×10^9
Bunch Length σ_z^* (m)	65×10^{-6}
Crossing Angle σ_c	5.5×10^{-3}
Disruption Parameters D_y, D_x	3.9, 0.03
Disruption Enhancement H_{Dy}, H_{Dx}	1.41, 1.00
Quantum Parameter Υ	0.11
Quantum Reduction Factor H_Υ	0.58
Beamstrahlung Parameter δ	0.021
Number of Bunches N_b	10
Bunch Repetition Rate f_b (Hz)	3600
RF Pulse Repetition Rate f_r (Hz)	360

Table V. Damping ring parameters for the design of Raubenheimer et al.[5]

Energy	1.8 GeV
Circumference	155 m
Momentum Compaction	0.00120
Tunes	$\nu_x = 24.37$, $\nu_y = 11.27$
RF Frequency	1.43 GHz
Damping Times with Wigglers on	$\tau_x = 2.50$ ms $\tau_y = 3.98$ ms
Repetition Rate	360 Hz
Current	100 bunches of 2×10^{10}
Emittance	$\epsilon_{nx} = 2.7 \times 10^{-6}$ m
Energy Spread	1.04×10^{-3}
Natural Bunch Length	5.2 mm

MAIN LINAC

Structure

The structure assumed for the design in Table III is a conventional $2\pi/3$ mode, constant impedance disk loaded structure with a somewhat larger disk aperture radius to wavelength ratio (a/λ) than the present SLAC structure. Z. D. Farkas[12] has obtained useful expressions for the important structure parameters (group velocity, elastance, peak surface field to gradient ratio and time constant $2Q/\omega$) for such a structure as a function of a/λ. However, as we will see in the next section, the transverse (deflecting) modes and the higher longitudinal modes must be strongly damped if a train of bunches is to be accelerated without excessive growth in transverse emittance or energy spread. Palmer[13,14] has proposed a structure design with slotted disks to damp these modes without substantially affecting the accelerating mode. A working group[15] at SLAC is looking into the theoretical and practical problems for this structure. Model tests at 2856 MHz are being compared with calculations using the MAFIA family of 3D codes. A few cells of structure at this frequency will be tested at high power to determine the high gradient behavior. Engineering design studies and manufacturing feasibility studies are in progress for a 17 GHz prototype.

A recent paper by G. Loew and J. Wang[16] gives a comprehensive summary of rf breakdown studies made to date. Reasonable models for the physical processes taking place near breakdown are also presented. The peak surface field that can be attained as a function of frequency for rf pulses on the order of 1–2 μs is given by $E_s(\text{MV/m}) \approx 195\,[f(\text{GHz})]^{1/2}$. For the rf structure parameters in Table III, this implies a maximum accelerating gradient of 320 MV/m at 17.1 GHz. The proper scaling with pulse length is not well understood, but the maximum gradient at 60 ns should be considerably higher, probably in excess of 500 MV/m.

RF Power Sources

Using the 1.2 MV, 1 kA beam from the SNOWTRON linear induction accelerator at LLNL, a series of experiments have been carried out with the goal of producing hundreds of megawatts of peak rf power at a frequency on the order of 10 GHz and a pulse length on the order of 50 ns. The current status of these "relativistic klystron" experiments is summarized in Ref. 17, and by R. Miller at this conference.[18] To date a peak power of 200 MW has been attained at 11.4 GHz, although the flat top of the rf output pulse was very short. Recent experiments[18] have shown that one source of this pulse shortening, anamalous beam loading in the rf cavities, can be cured by reducing the magnetic focusing field in the neighborhood of the cavities using appropriately placed ferromagnetic shielding. Transient effects are also important in determining the rf output pulse shape. These effects have been analyzed using a code developed by T. Lavine.[19]

The relativistic klystron achieves high power primarily by means of a very high beam voltage. An alternative approach is to keep the beam voltage low (less than 500 kV) and increase the current either by means of many parallel round beams or by a sheet beam. The first approach is taken by R. Palmer and R. Miller in their "cluster klystron".[20] In this device 126 beams are arranged in a honeycomb pattern. At 400 kV and 20 A per beam, a total of 750 MW of rf power is produced. The perveance per beam is low (0.08×10^{-6}) so that good efficiency can be expected ($\approx 75\%$). The sheet beam klystron[21] is an example of the second approach. A wiggler-focused sheet beam at 200 kV and 1 kA produced 100 MW of rf output power at 11.4 GHz from this device in a simulation using the computer code MASK. Other forms of sheet beam devices are possible which can in principle produce 100–200 MW per device in the 10–17 GHz frequency range.[22]

The devices mentioned in the preceding paragraph exist as yet only on paper and are in addition somewhat exotic. A project is underway at SLAC to see if a more-or-less conventional klystron can be built which will produce 100 MW at 11.4 GHz.[23] The tube operates at 440 kV and uses a combination of electrostatic and magnetic beam compression to achieve a reasonable cathode loading. K. Eppley[24] has simulated the dynamics of this tube, and finds that an efficiency of 43% is possible with a double output cavity. Diode tests on the tube should begin early in 1989. Eppley[25] has also investigated the general problem of self-consistent simulations for high power klystrons.

RF Pulse Compression

RF sources which deliver a peak power less than 500 MW or so will need to be followed by rf pulse compression to meet the peak power requirement for the TLC. A scheme for rf pulse compression, the Binary Peak Power Multiplier (BPM), is under development at SLAC. The principle of the BPM method is described in Ref. 26, and some low power measurements to test the basic theory are described in Ref. 27.

Assembly of components for a true BPM prototype system operating at 11.4 GHz, which will compress 320 ns to 40 ns in three stages, is now underway. The experiment will test the insertion loss of components (couplers, delay lines, 180° turnarounds and transitions), the overall power gain of the system, and effects due to dispersion and mode conversion. Initial measurements at low power will be reported[28] early next year. The expected compression efficiency is 80–85%, giving a peak power gain of 6.5–7.0. The next step will be to make the system vacuum tight so that it can be tested at high power, possibly using the 100 MW klystron mentioned above which is now under development.

BEAM DYNAMICS

Bunch Compression

In order to reach the short bunches required at the final focus, starting with a bunch length on the order of 5 mm in the damping ring, two stages of bunch compression are required. As in the SLC, a bunch compressor rotates the phase ellipse 90° in phase space to reduce the bunch length at the expense of a larger energy spread. A typical scenario for the TLC is outlined in Table VI. The numbers are approximate; for example, the energy of the damping ring may well be closer to 1.5 GeV rather than the 1.8 GeV for the design given in Table V. An attempt has been made to include the dilution factors mention previously. Kheifets et al.[29] have worked out a preliminary design for such a compression system.

Table VI. Bunch Compression in the TLC.

System	Energy (GeV)	N	σ_z (mm)	σ_p/p
Damping Ring	1.5 ± 0.3	2×10^{10}	7.0*	1×10^{-3}
Compressor #1	1.5	$1.7 \times 10^{10*}$	0.7	$1.2 \times 10^{-2*}$
Preaccelerator (2.856 GHz)	$1.5 \rightarrow 15$	1.7×10^{10}	0.7	1.2×10^{-3}
Compressor #2	15	1.7×10^{10}	0.07	$1.4 \times 10^{-2*}$
Main Linac (17 GHZ)	$15 \rightarrow 500$	$1.4 \times 10^{10*}$	0.07	5×10^{-4}

* Includes emittance dilution or particle loss.

Single Bunch Beam Dynamics

A number of deleterious effect which can lead to transverse emittance growth in the main linac have been summarized by Ruth.[30] These effects have been taken into account in deriving the parameters in Table I.

In recent months a series of experiments on the SLC have shown that BNS damping can significantly reduce the single bunch emittance growth due to transverse wakefields. The theory and simulation results for the SLC will be reported by K. Bane,[31] and the measurement results by Seeman et al.[32]

Multibunch Dynamics

In the TLC design envisioned here, a train of ten bunches spaced twelve wavelengths apart must be accelerated in the main linac. Long-range wake potentials can cause unacceptable growth in transverse emittance and energy spread between the first and last bunches in this train. If the wakefields in a given mode with wavelength λ_n are to decay by $1/e$ from one bunch to the next, the Q of the mode must be less than $12\pi\ (\lambda_0/\lambda_n)$, where λ_0 is the wavelength of the accelerating mode. A detailed analysis of transverse multibunch emittance growth in linacs has been made by Thompson and Ruth.[33–35] It is suggested that the Q of the lowest deflection mode be reduced to 20–30 to prevent undue emittance growth.

In a train of N_b bunches, beam loading would ordinarily produce an energy difference between the first and last bunch on the order of $\eta N_b/2$, where η is the fraction of energy extracted per bunch. For the TLC this would be about 13%, certainly unacceptably large compared to the final focus requirement of about 3×10^{-3}. By injecting the first bunch in the train before the accelerating structure has been filled with rf, this spread can be greatly reduced. Details of such an energy compensation scheme have been worked out by Ruth.[36]

Long range wakefields from higher order longitudinal modes will also contribute to the multibunch energy spread. Details remain to be worked out; however, initial estimates[37] indicate that a Q on the order of 100 is acceptable for these modes.

FINAL FOCUS AND BEAM-BEAM PHYSICS AT THE INTERACTION POINT

Final Focus

K. Oide[37] has worked out the detailed optics for a flat-beam final focus system. In a recent design,[39] he finds that for vertical and horizontal emittances of 2.5×10^{-8} m and 2.5×10^{-6}m, a beam size on the order of 1×240 nm can be achieved. These parameters are not quite consistent with those for the TLC design given in Table I, but the analysis indicates that beam of the required size and aspect ratio can be produced at the interaction point by a carefully designed final-focus optics which have been checked by tracking. In Oide's design, the length of the system is 2×300 m, the free IP space is 2×40 cm, the vertical half aperture of the final quadrupole is 0.23 mm, and the momentum bandwidth is $\pm 3 \times 10^{-3}$. Oide also takes synchrotron radiation into account in his design, and shows in fact that it imposes a serious limit on the focusing that can be achieved.[40]

Beam–Beam Physics

Using K. Yokaya's beam-beam simulation code ABEL, Chen and Yokaya[41,42] have studied the disruption effects in the collision of both round and flat beams. The luminosity enhancement and the maximum disruption angles are obtained as a function of both the disruption parameter D and an emittance parameter $A = \sigma_z/\beta^*$. For flat beams with typical values of A, they find that the luminosity degrades least rapidly with offset if the disruption parameter is in the range $D_y \sim 5$–10.

Chen and Yokaya[43,44] have studied beamstrahlung effects, both analytically and by simulation. Using a different theoretical approach, Drell and Blanckenbecler[45,46] have also studied quantum beamstrahlung. Their results are in substantial agreement with the usual Sokolov–Ternov formulation. Depolarization in the beam-beam collision has also been considered,[47] and found to be acceptable for the TLC parameters.

A final interaction region effect that must be taken into account is the multiple bunch crossing instability.[48] In this effect, the bunches of one beam which are leaving the interaction point give transverse kicks to the bunches of the opposing beam which are still moving toward the IP. The luminosity will not be degraded significantly if the constraint $(N_b - 1)D_x D_y \leq 2$ is fulfilled.

FINAL FOCUS TEST FACILITY

The present SLC is the most important test bed for future linear collider development at SLAC. Many aspects of the SLC provide invaluable experimental reference points for future collider design, for example damping ring performance, linac beam dynamics, linac instrumentation and control, and final focus diagnostics. However, a facility separate from the SLC is still desireable which can contribute to future collider development in two critical areas: final focus and beam instrumentation. To meet this need, a Final Focus Test Facility (FFTF) is being proposed at SLAC. A detailed design proposal for this facility, to be ready by the end of this year, is being prepared under the direction of D. L. Burke and J. M. Paterson.

The optics for the FFTF have been calculated by K. Oide.[49] The facility will be in the straight-ahead beam in the research yard at SLAC. The system is designed to handle flat beams with emittance ratios of 0.1 and 0.01, and a beam current of 1 $\times$ 10^{10} at 10 Hz. At the lowest vertical emittance (3 $\times$ 10^{-7} m) values of $\beta_y^* = 40$ μm and $\sigma_y^* = 13$ nm are calculated. The facility will be used for tests on final-focus optics and optical corrections, and for beam instrumentation.

ACKNOWLEDGEMENTS

The work at SLAC on future linear colliders involves the efforts of a large number of people, although only a few of them are able to devote more than a small fraction of their time to this program. The list of authors in the references which follow will serve as a general acknowledgement. The leadership of J. M. Paterson and the participation of Robert Palmer and Ronald Ruth in all aspects of the TLC R&D program merit special acknowledgement.

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