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Linear Collider Research and Development at SLAC, LBL and LLNL*

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1. INTRODUCTION

The study of electron–positron (e^+e^-) annihilation in storage ring colliders has been very fruitful. It is by now well understood that the optimized cost and size of e^+e^- storage rings scales as $E^2_{\rm cm}$ due to the need to replace energy lost to synchrotron radiation in the ring bending magnets. Linear colliders, using the beams from linear accelerators, evade this scaling law. The study of e^+e^- collisions at TeV energy will require linear colliders. The luminosity requirements for a TeV linear collider are set by the physics. The natural scale of electroweak cross sections is

$$R_0 = \frac{4\pi\alpha^2}{3s} \approx 0.1 \text{ pb} \frac{1 \text{ TeV}^2}{E^2_{\rm cm}} \quad . \tag{1}$$

A goal of $10^4 R_0$ units per year at 1 TeV requires a luminosity of order $10^{34}\text{cm}^{-2}\text{sec}^{-1}$.

Advanced accelerator research and development at SLAC is focused toward a TeV Linear Collider (TLC) of 0.5 to 1 TeV in the center of mass, with a luminosity of 10^{33} to 10^{34}. The goal is a design for two linacs of less than 3 km each, and requiring less than 100 MW of power each. With a 1 km final focus, the TLC could be fit on Stanford University land (although not entirely within the present SLAC site). The emphasis is on technologies feasible for a proposal to be framed in 1992.

Linear collider development work is progressing on three fronts: delivering electrical energy to a beam, delivering a focused high quality beam, and system optimization. Sources of high peak microwave radio frequency (RF) power to drive the high gradient linacs are being developed in collaboration with Lawrence Berkeley Laboratory (LBL) and Lawrence Livermore National Laboratory (LLNL). Beam generation, beam dynamics and final focus work has been done at SLAC and in collaboration with KEK. Both the accelerator physics and the utilization of TeV linear colliders were topics at the 1988 Snowmass Summer Study.

2. ENERGY DELIVERY

2.1 Linear Accelerator Technology

The first issue to be addressed in linear collider design is whether conventional linac technology can reach 1 TeV. Most present electron linear accelerators, e.g., SLAC, are based on disk loaded copper waveguides driven by microwaves from klystrons. Tests at SLAC with short copper accelerating structures have reached 144 MeV/m at the SLAC operating frequency (2856 MHz) before breakdown [1]. The breakdown limit appears to grow as $\sqrt{f}$, so at six times the SLAC frequency the gradient would be 353 MeV/m, which is more than adequate to reach 500 GeV in 3 km.

Linear colliders operate with picosecond bunches, and thus require RF power only for short pulses. Traveling wave linac structures have a tradeoff between filling speed (group velocity) and gradient per unit power, controlled by the diameter of the beam holes in the disks. Large iris holes give short filling times, so less power is lost to the copper walls and terminating loads. However, the same amount of energy must be stored in the structure, so the peak power requirement is increased. Higher gradients per unit peak power can be achieved at shorter wavelength, since this allows reduced waveguide diameter which essentially focuses the power into a smaller volume, increasing the electric field.

A short wavelength high group velocity TLC linac design with 186 MeV/m gradient would require 590 MW/m of peak power. Present SLAC klystrons produce up to 67 MW peak power.

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The peak power of conventional klystrons decreases as the wavelength decreases, because less electron beam power from a conventional electron gun can be compressed into the smaller beam tube diameter required at short wavelength. Thus, it seems unlikely that conventional klystrons could economically supply high peak power at short wavelength.

2.2 RF Pulse Compression

One method of increasing peak power is RF pulse compression. The SLC at SLAC uses a system based on RF cavities called SLED. However, SLED is limited to a factor of 9 in power regardless of pulse length or cavity Q. A new technique, called binary energy compression (BEC), can in principle give arbitrary gain [2]. Two RF sources feed long pulses into a dual output hybrid coupler with relative phases such that their outputs are first combined into a low loss waveguide delay line. Halfway through the pulse, just as the leading edge of the pulse comes out of the delay line, the phases are changed to direct the combined power through a short waveguide rather than the delay line. Both prompt and delayed pulses enter another hybrid coupler, where they are combined into a half-length pulse with twice the power. This pulse may be directed to one of the two hybrid output ports for use directly, or both ports may be used for another stage of compression. Any number of stages may be cascaded, each requiring half the delay of the previous stage. All of the phase changes can be done by low power phase shifters at the klystron inputs. The low-loss delay line diameter scales down with wavelength, and the length scales down with RF pulse length, so binary energy compression is well matched to linear collider operation at short wavelength and short pulse length. Low power tests of the binary compression concept will begin soon at SLAC, with high power tests to follow.

2.3 Induction Drivers

Another approach to high peak power is DC pulse compression. Metallic glass saturable inductors are used at LLNL as switching elements in multistage magnetic pulse compressors to drive induction electron linacs [3]. A long DC pulse charges a capacitor which is isolated from the load by a saturable inductor. The inductor is designed to saturate just as the capacitor is fully charged. Saturation causes reduced inductance, so the capacitor discharges rapidly into the load. The load receives a pulse with the original charge and voltage, but higher current delivered over a shorter time. Since the load may be another capacitor and saturable inductor stage, the current may be multiplied manyfold at constant voltage.

The Accelerator Research Center (ARC) linac at LLNL produces pulsed 1.2 MeV beams at 1 kA. The ARC linac has been used in place of conventional klystron electron guns and pulse modulators in experiments with SLAC-built klystrons [4]. The first experiment (Fig. 1) used a tube which had produced 22 MW of 8.6 GHz RF power as a conventional klystron at its 330 kV design voltage. Using the beam from ARC at up to 800 MV, the peak power increased to 75 MW. At higher voltage the RF power decreased, due to poorer match between the relativistic beam parameters and the klystron cavity spacing.

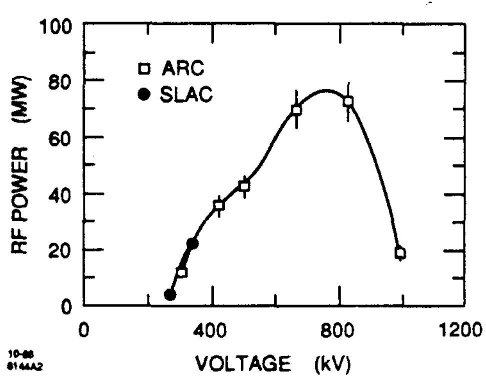

Fig. 1. 8.6 GHz RF power vs beam voltage for klystron at SLAC using conventional modulator, and using ARC linac at LLNL.

The latest experiment uses an 11.4 GHz klystron, specifically optimized for 1.2 MV operation (Fig. 2). It has achieved 100 MW pulses 50 nsec wide, and shorter pulses of 200 MW. A 26 cm long scaled SLAC-type linac structure has been driven by this klystron, reaching an accelerating gradient of 144 MeV/m.

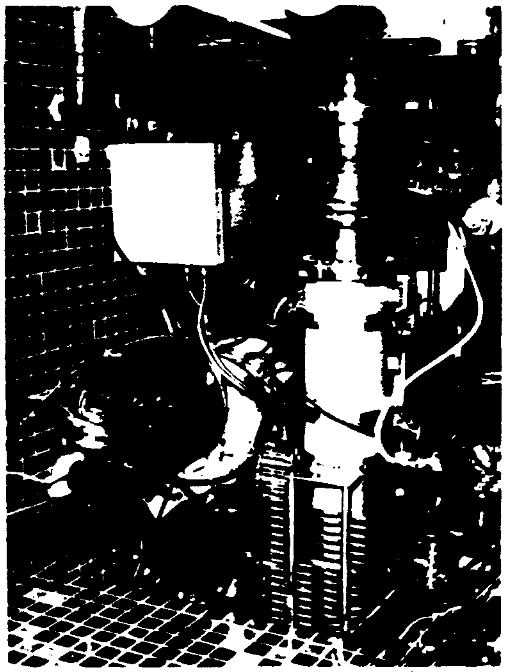

Fig. 2. 11.4 GHz SLAC klystron mounted on ARC linac. Beam exits linac (right), is bunched then decelerated by klystron, and is stopped in water-cooled dump (left).

While high peak RF power has been relatively simple to demonstrate in the LBL-LLNL-SLAC experiments, practical application will require better solutions to the matching problem. Magnetic pulse compression gives high peak DC power in the form of high current at modest voltage. Electron beam bunching in a klystron works best at low current, where space charge effects are small, and extracting power from the bunched beam with an RF cavity works best at high voltage, because the cavity voltage cannot exceed the beam voltage. Essentially, an induction cell driven by magnetic pulse compression is a low impedance source, while a klystron is a high impedance load. One approach to the matching problem is the equivalent of putting many loads in parallel. Klystrons with sheet or ring beams, or many parallel beamlets, could bunch high current beams with less interference from space charge. Another approach is to put many induction cells in series, making a relativistic beam more resistant to space charge forces. In the two-beam accelerator concept [5], a fraction of the beam power is extracted, then the beam is reaccelerated for further power extraction.

3. BEAM DELIVERY

3.1 Final Beam Spot

The logic of linear collider optical design is best followed upstream from the final beam spot back to the beam sources. Storage rings recycle their beam power (apart from synchrotron energy loss), while linear colliders throw it away, so storage rings can have much higher collision repetition rates per unit of power. To have the same luminosity per unit expended power, a linear collider must have a much smaller colliding beam area than a storage ring. Small beam area is achieved by low ϵ (emittance or transverse phase space), low β^* (achieved by strong focussing at the interaction point), and careful minimization of dispersion and chromatic or geometric aberrations.

The large peak bunch current in a small size bunch results in large magnetic fields around the bunch. Large fields cause synchrotron radiation when the bunches cross (beamstrahlung), and make oppositely charged beams focus each other (disruption). Some disruption is beneficial to luminosity, but beamstrahlung adds to the beam energy spread, and large disruption makes the outgoing beam difficult to contain.

The TLC parameters call for a flat final beam spot, with $\sigma_x = 380$ nm, and $\sigma_y = 2.9$ nm. The reason for the large aspect ratio is that for a given bunch current, the magnetic field is smaller near a flat bunch than near a round one, which reduces beamstrahlung and disruption. Storage rings and damping rings produce flat beams ($\epsilon_y \ll \epsilon_x$) naturally, since horizontal betatron oscillations are excited by synchrotron radiation, but vertical betatron oscillations can damp out completely. Also, since quadrupole magnets focus in one plane and defocus in the other, fewer quads are required for a flat beam final focus design.

3.2 Final Focus

A very strong final quadrupole magnet is required to produce the small spot size. The TLC parameters require a final quad with a gradient of 875 kG/cm. To achieve this with a poletip field of 14 kG requires an aperture of only 160 microns. The disrupted outgoing beam will not fit into the opposite quad aperture, so the beams cross at a 3 mrad angle in the x plane, which is sufficient for the outgoing beam to fit between quad poles. The TLC parameters call for a bunch length σ_z of only 70 microns, so the angle costs little luminosity. The free space from quad to interaction point (IP) is only 48 cm, putting it deep inside the detector, but the quad is so small that a cantilever support can be kept within a 10° cone. Passive seismic isolation similar to that used in the Caltech gravity wave detector would be adequate to keep the quads stable to a fraction of the final beam size. Calculated backgrounds from disrupted beam and synchrotron radiation would allow a vertex detector as close as 500 microns from the IP. The mean beamstrahlung energy loss is 13%. Monte Carlo studies of TeV e^+e^- events indicate that up to 25% mean beamstrahlung energy loss and a 10° hole in acceptance in the forward and backward direction can be tolerated for most physics [6].

A flat beam TLC final focus system, including chromatic corrections, has already been designed [7]. There is a project underway at SLAC to build a scaled down version of this design as a Final Focus Test Facility (Fig. 3) in the old 0° C-Line. With the measured ϵ_x of the damped SLC beam, the final spot should have $\sigma_x = 2.4$ microns at 50 GeV. The SLC damping rings produce a round beam only because they are intentionally run on a coupling resonance. If ϵ_y can be reduced to 1% of ϵ_x, as it can be in most storage rings, and has nearly been achieved in tests at SLC, then the final σ_y should be only 12 nm.

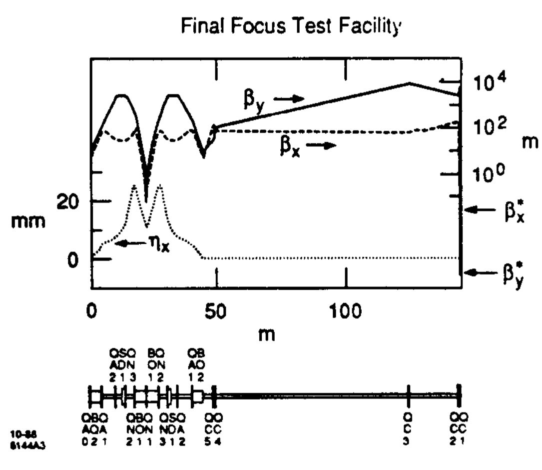

Fig. 3. Final Focus Test Facility design. Dispersion (η) is plotted with linear scale at left. Vertical (β_y) and horizontal (β_x) beta functions are plotted with log scale at right. Magnets are plotted below the meter distance scale.

3.3 Main Linear Accelerator

The fundamental beam dynamics issue in a TLC linac is emittance growth due to transverse wakefields. If the head of a bunch is off axis in an accelerating structure, it excites transverse cavity modes called wakefields which deflect the tail of the bunch further off axis. Transverse wakefields are smaller for small bunch populations, small bunch lengths, and large linac iris openings. Wakefields can be substantially cancelled by a method often called Landau damping. and more properly called Balakin-Novokhatsky-Smirnov (BNS) damping [8], which has been sucessfully tested recently in the SLC. If the bunch is accelerated off the RF crest, such that the tail is at a lower energy than the head, the linac quadrupole magnets focus the tail more than the head. When the beam is off axis, the extra magnetic deflection of the tail toward the linac axis from the quads can be made to roughly cancel the electric deflection away from the linac axis from the wakefields. (The beam is accelerated on the other side of the RF crest in the last sectors of the linac to remove the large energy spread.)

An obvious way to improve the luminosity to RF power ratio of a linear collider would be to accelerate multiple bunches during the same linac RF pulse. However, wakefields would linger in the linac and deflect the later bunches, particularly for the short bunch separation required for short RF pulses. Two new ideas may make multiple bunch operation feasible. One idea is wakefield damping, in which slots in the waveguide couple transverse modes out from the accelerating region to a place where they can be absorbed [9]. This can be done without significant penalty to the longitudinal accelerating mode. The other idea is wakefield tuning, in which the fundamental transverse mode is tuned relative to the accelerating mode. such that the trailing bunches can be placed at zero crossings of the transverse mode [10].

3.4 Injector Complex

The injector complex is the set of components required to prepare the bunches for injection into the linac. The TLC parameters call for an injector complex similar to that of the SLC, with some refinements (Fig. 4). Damping rings are required to reduce the bunch emittance before injection into the linacs. The ring energy is set by balancing emittance growth from synchrotron radiation and from intrabeam scattering, with the optimum near the 1.2 GeV energy of the SLC rings. Rings with tenfold smaller ϵ_x than the SLC rings seem possible by weakening the bends and strengthening the focussing, thus minimizing emittance excitation from synchrotron radiation. Skew quadrupoles to null out x-y coupling could reduce ϵ_y to 100 times less than ϵ_x (200:1 has been observed in synchrotron light source rings). Wiggler magnets will probably be necessary to reduce the damping time, and residence times of several linac cycles, or multiple rings, may still be necessary. Higher RF frequency will be needed for multiple bunch operation [11].

The natural σ_z of a damping ring results in large transverse wakefields in a linac. In the SLC, a head-tail energy difference in the curved beam line from ring to linac allows the tail to catch up with the head. The short wavelength main TLC linac requires an even shorter bunch, so the first TLC linac sectors will run at longer wavelength, and will be followed by another stage of bunch compression in a curved beam line.

Electron and positron source requirements for the TLC are not substantially different than for SLC. Polarized electron beams have been available from the SLAC linac for years, and will be used in the SLC. The TLC is even better suited to polarized beams, since the problem of spin precession in arcs is avoided. Since positron yield scales with beam energy, the high energy main TLC electron beam would give very high yields. A separate lower energy high current linac could also be used, which would have the operational advantage of decoupling the e^- and e^+ linacs completely.

4. PARAMETER OPTIMIZATION

Many of the parameters of linear collider design are highly coupled. For instance, the linac structure, the power supply system, alignment tolerances and the final focus system all either affect or are affected by the beam energy spread. There are physical or technological limits on many design parameters. It is a difficult task to find a set of parameters that is self-consistent, i.e., satisfies the physical constraints, and more difficult still to satisfy the technological constraints. R. B. Palmer has developed a computer program incorporating the various constraints [12], and the parameters cited above and in Table 1 are results from that program as of Summer 1988 [13]. (The constraints and thus the parameters are refined over time as work progresses toward a genuine design.) The program has also been used to calculate the luminosity of an intermediate linear collider (ILC), a TLC stage with full length linacs but with only one-fourth of the RF power, thus half the energy.

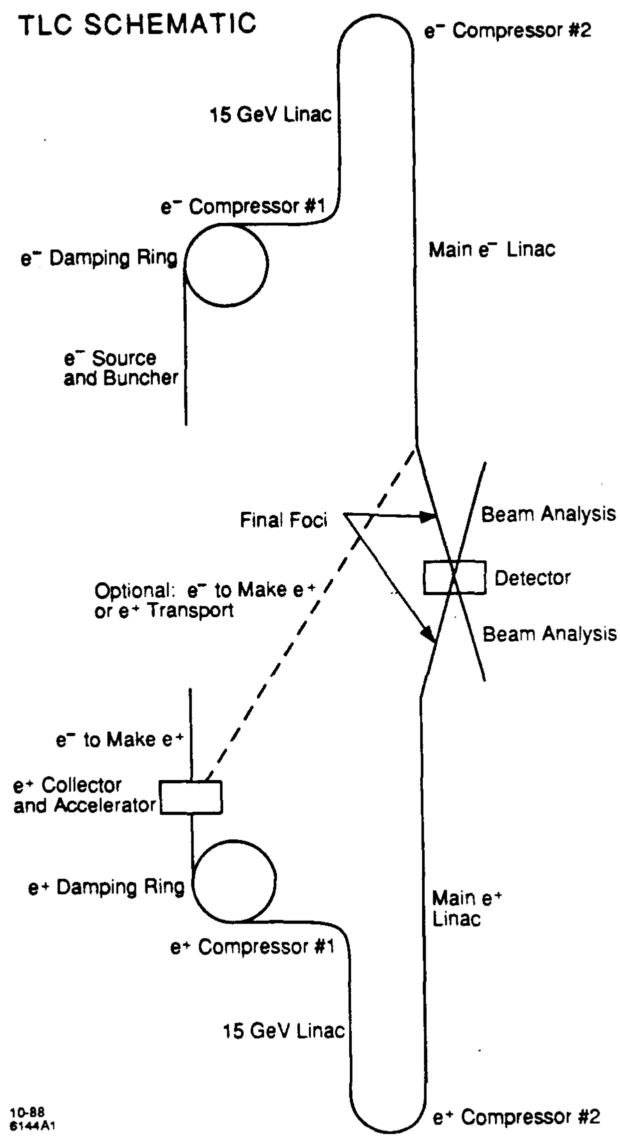

Fig. 4. Schematic representation of TeV Linear Collider (not to scale). e^- beam is accelerated to 1.5 GeV in source and buncher, then stored and cooled in damping ring. Damped bunches are extracted, compressed, and injected into a long wavelength 15 GeV linac. A second bunch compressor precedes injection into the main linac. e^- collide with e^+ at small angle (exaggerated here), then enter beam diagnostic instrumentation before dump. e^+ may be produced by separate low energy linac or by main e^- linac, but otherwise follow an identical path.

Table 1. TLC and ILC parameters.

Parameter	TLC	ILC	Units
E_{cm}	1000	500	GeV
Luminosity	6×10^{33}	1.1×10^{33}	$cm^{-2}sec^{-1}$
AC Power	204	50	MW
Peak RF Power	590	150	MW/m
Gradient	186	93	MeV/m
Beamstrahlung	10	2	%
Vertical Disruption	5	3.9	
Horizontal Disruption	0.05	0.04	
Vertical Beam Size	2.9	3	nm
Horizontal Beam Size	380	440	nm
Bunch Length	70	65	μm
Particles per Bunch	1.4×10^{10}	7×10^{9}	
Bunches per Fill	10	10	
Repetition Rate	360	360	Hz
RF Frequency	17.14	17.14	GHz
Total Length	7	7	km

Note that the ILC luminosity is about one-fourth of the TLC luminosity, but since the cross section is about four times higher according to Eq. (1), the event rate would be comparable. Palmer has also calculated parameters for linear colliders at 10 and 100 GeV with luminosities exceeding 10^{33} which present different technical challenges. An optimized 500 GeV linear collider could have a luminosity higher than the ILC, by differing from the TLC in more parameters than only the peak RF power level. Since the RF power source is one of most difficult technical challenges in the TLC parameters, it is encouraging that a healthy physics program could commence with RF power levels that appear not far out of reach for ILC energies, with a later upgrade to a full TeV as RF power technology matures.

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