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LINEAR COLLIDERS: THE LAST TEN YEARS AND THE NEXT TEN YEARS

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INTRODUCTION

Some of the most important discoveries and systematic studies in elementary particle physics have been made at electron-positron colliders. These include the discoveries and measurements of the properties of the C-quark and τ-lepton, the studies of B-mesons and gluons, the measurement of the number of light neutrinos, and precision measurements of electroweak parameters. These colliders are such powerful instruments because of the unique center of mass energy and initial quantum numbers, $J^{PC} = 1^{--}$, of e^+e^-annihilation, and backgrounds that are beam-related rather than being an unavoidable part of the total cross section.

Storage rings are limited in center-of-mass energy, E_{CM}, by synchrotron radiation. The synchrotron radiation energy loss per turn is

$$U_0 = \frac{4\pi r_e}{3} mc^2 \frac{\gamma^4}{\rho} \tag{1}$$

where γ is the beam energy in units of rest energy, mc^2, r_e is the classical electron radius, and ρ is the bending radius. The luminosity of a storage ring operating at the beam-beam limit is directly proportional to the total current, I_T, and beam energy

$$L = \xi \frac{I_T}{e} \frac{\gamma}{r_e \beta_y^*}. \tag{2}$$

In this equation, ξ is the beam-beam tune shift and β_y^* is the vertical beta-function at the collision point. Non-resonant cross sections fall as $1/\gamma^2$, and the synchrotron radiation power, $P_{SR} = I_T U_0$, must increase as γ^5 for a constant event rate.

LEP is the largest storage ring in the world; some of its parameters are given in Table I. These numbers together with the steep energy dependences of U_0 and P_{SR} lead to the conclusion that the size and cost of a storage ring collider with a center-of-mass energy much greater than that of LEP would be astronomical! Linear colliders avoid this energy limit by not bending the beams, and they extend the potential energy of e^+e^- collisions.

The cross section for producing μ-pairs is

$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{\pi\alpha^2}{3(mc^2)^2} \frac{1}{\gamma^2}. \tag{3}$$

This cross section is 87 fb at E_{CM} = 1 TeV, and $L = 10^{33}\text{cm}^{-2}\text{s}^{-1}$ at that energy would give 7.5 μ-pairs per day. All of the cross sections for producing point-like particles are proportional to the μ-pair cross section, and luminosity in the 10^{33} - $10^{34}\text{cm}^{-2}\text{s}^{-1}$ range is needed for the physics at roughly 1 TeV. This demanding requirement dominates high energy linear collider design.

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Table I LEP Parameters [1, 2]

Parameter	LEP I	LEP 200
Circumference	26,659 m	
Bending Radius, ρ	3,096 m	
Total Current, I_T	3.0 mA	
Beam Energy, E	55 GeV	95 GeV
Energy Loss/Turn, U_0	260 MeV/turn	2.31 GeV/turn
Synch. Rad. Power, P_{SR}	1.56 MW	13.9 MW
Peak RF Voltage	360 MV	2.7 GV
Nominal Luminosity	$1.7\times10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$2.7\times10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Linear colliders were first proposed by Maury Tigner in 1965,[3] but the interest in them heated up in the early 1980's when the implications of the energy limitation from synchrotron radiation was first appreciated in a concrete way. Until then it was easier to increase the size of storage rings rather than face the energy limit head-on. LEP made it clear that this approach had reached its end, and linear colliders would have to be developed to increase the energy of e^+e^- collisions.

The early 1980's was a period of great enthusiasm about linear colliders. The SLC had been approved and was under construction. A quick turn-on and a first year luminosity of $6\times10^{29}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ were projected.[4] In addition, people talked loosely about a linear collider that could do "SSC equivalent" physics at a fraction of the cost. These projections were beyond what could be supported by reasonable expectations, but the enthusiasm was critical because it set into motion a series of actions that are forming the three thrusts in linear collider development. These were:

1.- The construction, commissioning, and development of the SLC that has established the viability of linear colliders;
2.- The research and technology development aimed at an $E_{CM} = 0.5$ TeV linear collider that has opened up a new energy range for e^+e^- collisions;
3.- The establishment of the field of advanced accelerators and new particle acceleration techniques that hold out the possibility of e^+e^- collisions determining the energy frontier of particle physics in the future.

Traditionally that energy frontier has belonged to the hadron colliders where it hasn't been necessary to deal with synchrotron radiation. That has more than compensated for the constituent center-of-mass energy being lower than the beam center-of-mass energy. There are technically sound ways to reach constituent center-of-mass energies of several TeV with hadron colliders, but they will have reached an energy where storage rings become impractical after completion of the LHC. An innovation as novel as the linear collider for e^+e^- collisions would be needed to reach significantly higher energies, and e^+e^- linear colliders could determine the energy frontier in the future. That will require another step beyond the $E_{CM} = 0.5$ TeV collider that is the present focus of the linear collider community, and it is likely to require success with some of the directions being pursued by the advanced accelerator community.

The energy frontier is uncertain and insecure. Despite its outstanding science and technical merit the SSC failed because of a combination of politics, cost, and economic climate in the United States. The LHC has not been approved yet, and its construction is not assured. Political and economic issues similar to those for the SSC and LHC are certain to be in the future for linear colliders. To face them one needs to be optimistic that outstanding, large scientific projects will be supported and that methods for that support will be developed through the experience with the LHC, large fusion and space research projects, and the informal international collaborations developing linear collider designs .

THE SLC

The SLC was intended as a prototype linear collider and as an accelerator for particle physics. These are compatible because of the large cross section for producing Z's, $\sigma(e^+e^- \rightarrow Z) \approx 30$ nb. Demonstration of particulars such as small collision spots or high intensities were crucial steps in the development of the SLC, but, by themselves, they are not enough to prove the viability of linear colliders. That depends on sustained operation with good luminosity and low backgrounds with the demanding conditions set by a particle physics experiment.

The SLC had a long, difficult commissioning. It was the first of a new type of accelerator, and despite the best efforts of the designers, the difficulties of operating it were not appreciated beforehand. Many parameters including peak current, transverse emittances, and beam sizes were being pushed into new regimes simultaneously. Linear colliders are like hadron colliders in one way - any mistake made upstream is remembered and emittance preservation, β matching, dispersion matching, etc. are extremely important. This makes it difficult to achieve performance breakthroughs in many areas simultaneously. Problems in downstream areas such as the final focus can't even be seen until upstream areas are performing reasonably, and collision performance cannot be used to diagnose problems upstream until the downstream is performing reasonably. In many cases new diagnostics and techniques had to be invented and proved to make progress.

The complexity of the SLC is in a new regime also. The engineering standards for performance and reliability are stringent for a linear collider because there are a large number of components and few of them can fail or be operating out of specification without impacting performance. This is another factor that made the SLC commissioning difficult. New levels of equipment and beam diagnostics and control were needed. It took time for this to be realized and for these to be developed. Now they are part of everyday operation.

SLC commissioning is over, and the SLC is running as an accelerator for particle physics and as a prototype linear collider. The day-to-day operation and luminosity improvement programs are shaping many of the ideas about future linear colliders.

Table II and Figures 1, 2, and 4 summarize performance. There has been steady improvement in the average luminosity which reached a peak of 3.5×10^{29} $\text{cm}^{-2}\text{s}^{-1}$ early in the summer of 1993. The increase from 1992 to 1993 came from the synergy between SLC operation and work on future colliders which are based on flat beams, $\sigma_x >> \sigma_y$, to minimize backgrounds. Emittance preservation and focusing of flat beams with high order optical corrections need to be verified experimentally as part of the development of future colliders. The Final Focus Test Beam (FFTB) collaboration was formed to develop and test a prototype next generation final focus. They need flat beams for those tests, and in the process of delivering those beams it was found that the alignment, feedback and orbit bump techniques developed at the SLC performed better than expected. Invariant emittances well below the design value

Table II Typical SLC Parameters for the 1993 Run

Parameter		Value	
Energy	at End of Linac	46.5 GeV	
	at Interaction Point	45.59 GeV	($m_Z/2$)
Intensity	in Damping Rings	3.0 - 3.3 $\times 10^{10}$	
	at Interaction Point	2.8 - 3.0 $\times 10^{10}$	
Polarization		0.60 - 0.64	
Invariant Emittances	at End of RTL	3 - 4 $\times 10^{-5}$ m	horizontal
		0.3 - 0.4 $\times 10^{-5}$ m	vertical
	at End of Linac	4 - 5 $\times 10^{-5}$ m	horizontal
		0.5 - 0.9 $\times 10^{-5}$ m	vertical
Beam Size	at Interaction Point	2.6 μm	horizontal
		0.8 μm	vertical
RMS Bunch Length	at Interaction Point	1.0 mm	
RMS Energy Spread		0.3%	
Repetition Rate		120 Hz	
Luminosity	(see Figure 1)	0.2 - 0.35 $\times 10^{30}$ cm^{-2}s^{-1}	

of 3×10^{-5} m could be transported down the linac at an intensity of 3×10^{10} particles per bunch.[5] These results showed that it was possible to use flat beams in the SLC. The SLC arcs prevent running with truly flat beams but elliptical beams are possible, and the reduction in beam area (Figure 2) in 1993 came from that.[6]

With flat beams and the current SLC final focus the minimum vertical beam size is about 0.8 μm (Figure 3) and is dominated by a single third-order aberration, the

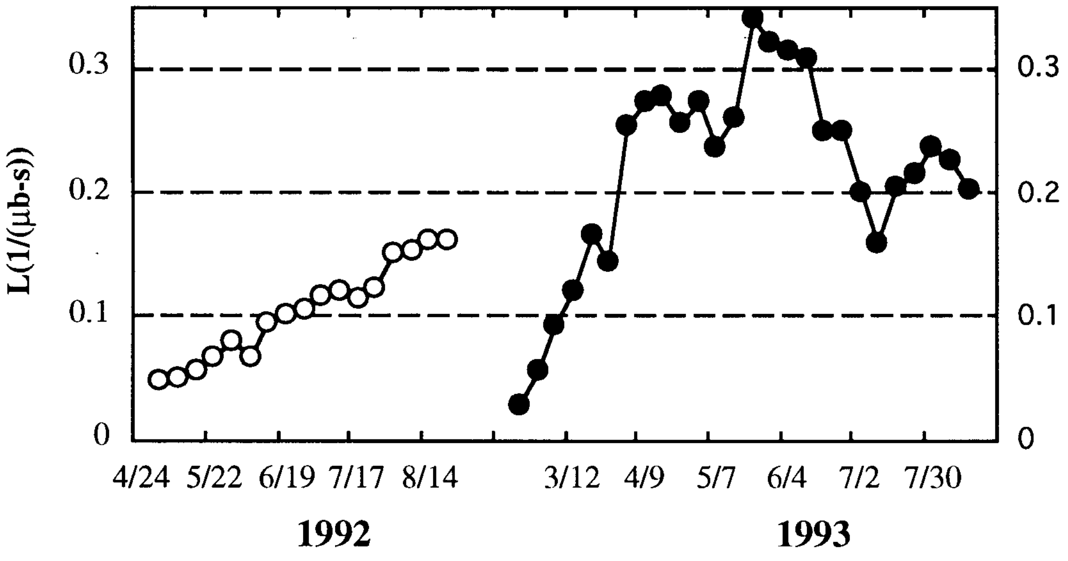

Figure 1. The average SLC luminosity (in units of 10^{30}cm^{-2}s^{-1}) in 1992 and 1993.

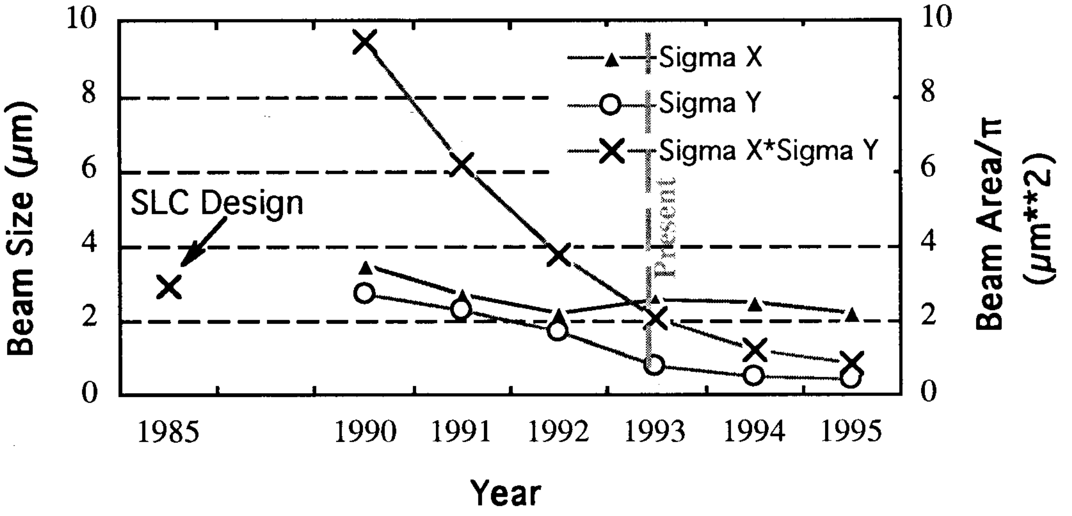

Figure 2. The transverse beam sizes and beam area at the SLC collision point. Past performance and future projections are shown.

$y'^2\delta^2$ term in the Hamiltonian (U_{3466} in TRANSPORT notation). This aberration can be controlled with an additional quadrupole in the chromatic correction section (CCS). A major SLC upgrade for 1994 is the installation of that quadrupole, some sextupoles to correct geometric aberrations in the final triplet, and additional optics and diagnostics to aid final focus tuning.[7]

The SLC has relied on developments for future colliders in making the performance improvement in 1993 and designing the 1994 upgrade. SLC operation in 1994 will address a vital concern for future colliders - can a highly corrected optical system be diagnosed and tuned fast enough and precisely enough to accommodate the continual changes in the incoming beam from the linac? This development is just one example of the importance of the SLC for future linear colliders.

The luminosity fell after the peak in the early summer due in part to a heat wave and interruptions to steady running. However, these factors alone cannot explain the reduced luminosity; possible causes include shifts in alignment due to the changing water table and deterioration of the vacuum in a section of the accelerator. These type of problems occur in any accelerator, and learning to diagnose and fix them quickly is key to good integrated luminosity. Some of the new final focus diagnostics were motivated by not being able to understand the luminosity decrease, and if they prove successful at quickly identifying problems, SLC operation will have added even more to the specifications of the diagnostics needed in any future collider.

The integrated luminosity is shown in Figure 4. The SLC has been operating with between 60% and 80% uptime, and the SLD experiment accumulated over 10,000 $e^+e^- \to Z$ events during the 1992 run when the electron beam polarization was $P \approx 22\%$. The first measurement of the left-right asymmetry in Z boson production, A_{LR}, was published based on those data.[8] The statistical uncertainty of that measurement is proportional to $1/(P\sqrt{N_{ev}})$ where N_{ev} is the number of events. The polarization and number of events were increased significantly in 1993 to 62% and 50,000, respectively, and there should be a new, precise measurement of A_{LR} and the Weinberg Angle based on those data soon. The SLC is meeting its goal of being an accelerator for high energy experiments.

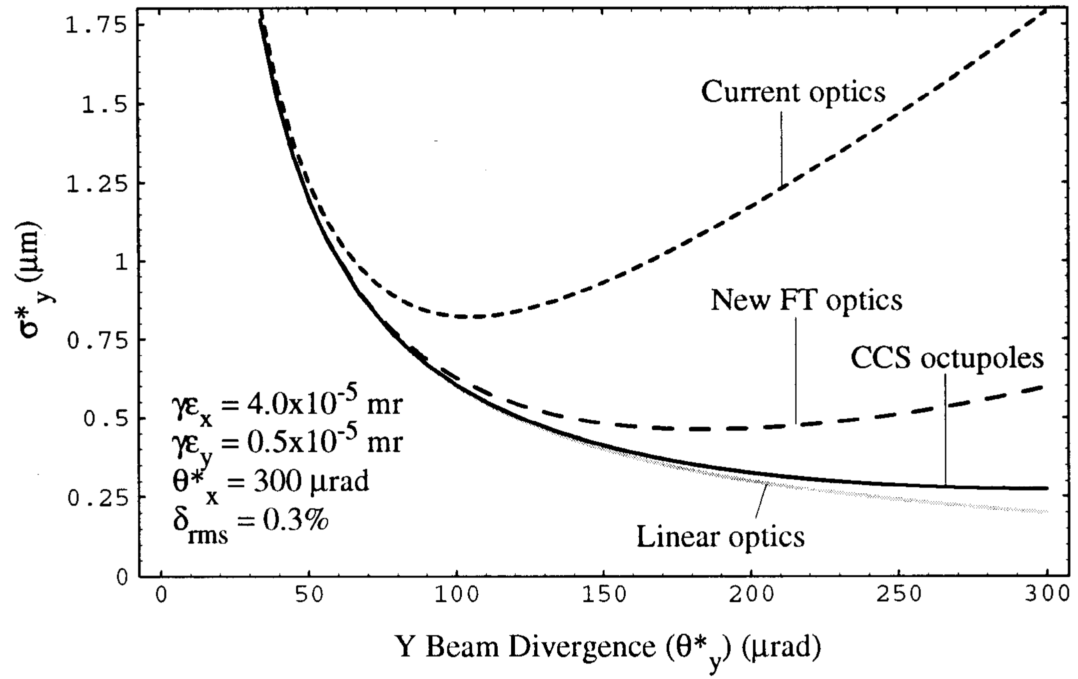

Figure 3. SLC final focus performance for the optics used in 1993 ("Current optics"), the upgrade being installed for 1994 ("New FT optics"), and for a possible future improvement ("CCS octupoles").[7]

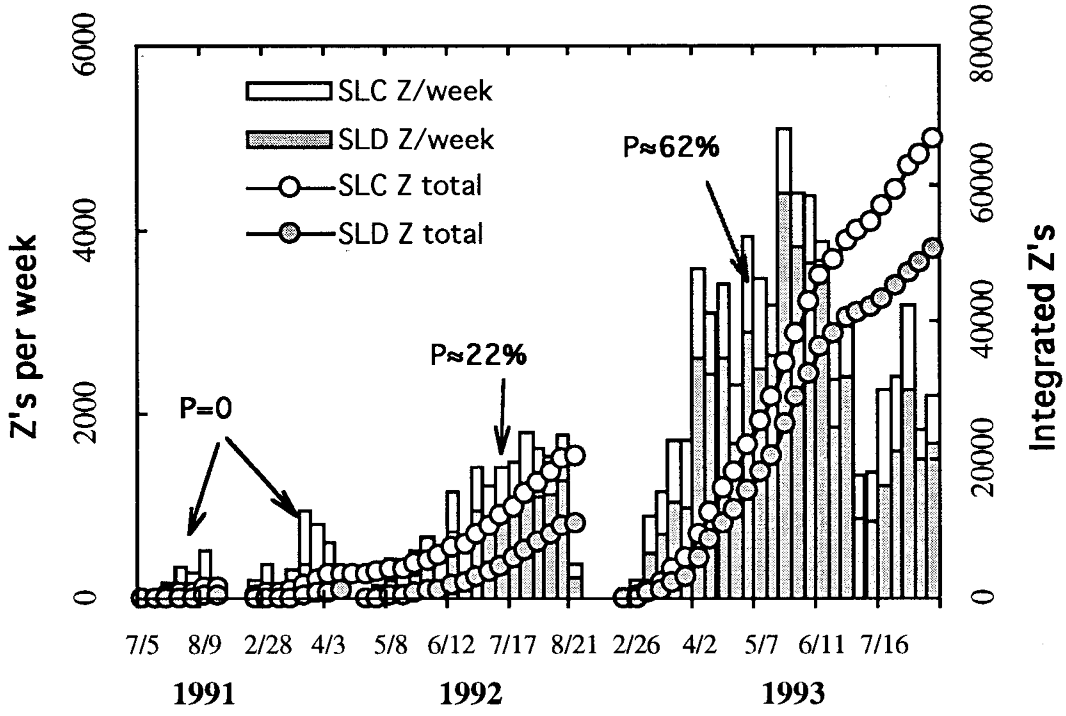

Figure 4. SLC performance for the past three years. The SLC numbers are based on beam current and spot size measurements from beam-beam deflections. The SLD numbers are the number of Z's recorded on tape.

The second major improvement nearing completion is replacement of the damping ring vacuum chamber. The damping ring bunch length increases due to potential well distortion starting at about 2×10^{10} particles per bunch, and the microwave instability threshold is 3×10^{10} per bunch. The transverse emittances are increased by potential well distortion because of the following. A longitudinal phase space rotation is performed in the Ring-To-Linac (RTL) transfer line interchanging energy spread and bunch length, so potential well distortion increases the energy spread in the RTL. The RTL must be chromatically corrected to preserve the transverse emittances,[9] and that correction is not as good and becomes more sensitive and difficult to maintain against drifts as the energy spread increases.

The microwave instability in the damping rings is the present SLC intensity limit. It manifests itself as a relaxation oscillation.[10] The beam radiation damps until the peak current exceeds the instability threshold; then the longitudinal phase space blows-up rapidly, in ~5 synchrotron oscillations, to a peak current that is below threshold. Radiation damping starts the cycle over again. The synchronous phase shifts during this oscillation because of the bunch length dependence of the higher mode losses. Shifts in the synchronous phase and bunch length affect the bunch rotation in the RTL and the phase of injection into the linac. Bunches extracted when the longitudinal phase space is changing rapidly are handled particularly poorly and can be so far off in energy that the backgrounds they create trip off the SLD detector. The only practical way to avoid this has been to restrict the maximum intensity to near the microwave instability threshold.

The present damping ring impedance is dominated by masks protecting bellows from synchrotron radiation, transitions between different chamber geometries, and distributed ion pump slots. This impedance is being reduced by a factor of five through a combination of precision manufacturing and magnet alignment to reduce the number of bellows and numerically controlled machining to make the transitions more gradual and the ion pump slots narrower. With this new vacuum chamber the potential well distortion and microwave instability thresholds will be well above the charge that the linac can accelerate to 46.5 GeV, the energy needed for collisions at $E_{CM} = m_Z$.

It is projected that the final focus and damping ring upgrades will bring the SLC luminosity to $L > 10^{30}\text{cm}^{-2}\text{s}^{-1}$ and the event rate to over 10,000 Z's per week by decreasing the vertical size to $\sigma_y \leq 0.5$ μm and increasing the intensity at the collision point to $3.5 - 4\times10^{10}$. It is difficult to predict parameters and performance precisely because the upgrades will remove the present spot size and intensity limits and there isn't any experience yet to know the next limits. There should be substantial disruption that should increase the luminosity by roughly 30%.

A wide range of knowledge has been learned from the SLC. It can be characterized as:

1.- The development of particular components or systems that were pushing the state-of-the-art and are now the standard for comparison and the base for the next developments. Examples are the 60 MW klystrons, the positron target and capture system, and the polarized electron gun.

2.- Techniques that have proven their value in SLC operation and have been incorporated as central features of the next generation collider. These include beam based alignment and optics diagnostics, techniques for emittance preservation, and adaptive feedback systems.

3.- Beam dynamics including experiments in emittance preservation, polarization control, and damping ring beam instabilities. The anticipated observation of disruption next year will be the first experience with beam-beam effects in linear colliders.

4.- Design philosophies for future colliders. Linear colliders are complex, and that complexity is bound to increase with increasing energy. The interdependence of the SLC accelerator systems made commissioning difficult, and it still shows up today in subtle ways such as trips of the SLD drift chamber high voltage being the first, most evident manifestation of the damping ring microwave instability. Reliability and quality assurance (QA) have unfortunate, bureaucratic connotations, but specifying reliability and treating it on a par with performance and cost would have decreased the SLC commissioning time significantly. Finally, thorough diagnostics of the beam and equipment has a handsome payoff. The SLC control system is designed to routinely measure and log an enormous amount of data such as beam emittances, power supply control and readback signals, and temperatures in all parts of the accelerator. These data are invaluable for finding and fixing problems which often are not evident when they first occur.

$E_{CM} = 0.5$ TEV[11]

Linear collider design and development have become focused on $E_{CM} = 0.5$ TeV and $L \sim 5\times10^{33}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$. The consensus on these general parameters has come about because they combine technical feasibility with substantial particle physics including studies of the top quark, possible studies of electroweak symmetry breaking phenomenon, and large enough increases in center-of-mass energy and luminosity to reveal the totally new and unexpected. A recent ICFA Seminar strongly endorsed a 0.5 TeV linear collider as the next natural step for high energy physics after the LHC and as an important opportunity for international collaboration.[12]

There are diverse approaches to meeting these general objectives. The diversity arises from different judgments about the ease of developing new and improving existing technology, costs, extension to higher energies, experimental backgrounds, center-of-mass energy spectrum, tolerances, and beam power.

Selected parameters are given in Table III which is based on a compilation made by G. Loew at the LC-93 Conference and is reproduced with his permission.[13] The colliders described in that table are:

1.- TESLA (being developed by an international collaboration) which is based on superconducting RF. All the others would use room temperature RF.

2.- SBLC (an international collaboration centered at DESY/Darmstadt) which uses S-band (3 GHz) RF where there is extensive operating experience.

3.- NLC (SLAC) which uses higher frequency X-band (11.4 GHz) RF in a modulator-klystron-accelerator configuration similar to S-band linacs.

4.- JLC-I (KEK) which has three frequency options, S-band, C-band (5.7 GHz), and X-band. Multiple bunches are accelerated in each RF pulse as they are in TESLA, SBLC, and NLC.

5.- VLEPP (INP) which employs a single high intensity bunch rather than multiple bunches.

6.- CLIC (CERN) which is a "two-beam" accelerator with klystrons replaced by an RF power source based on a high-current, low-energy beam traveling parallel to the high energy beam.

The AC power is large for any of the colliders, and energy efficiency is important. One way to achieve good efficiency is by accelerating multiple beam bunches per RF pulse.

For example, in the SBLC a 150 MW, 2.8 μsec long RF pulse powers two 6 m long sections to a gradient of 17 MV/m. The beam has 125 bunches with 2.9×10^{10}

Table III Selected Linear Collider Parameters for $E_{CM} = 0.5$ TeV
(G. Loew, LC93)[13]

Parameter	**TESLA**	**SBLC**	**JLC-I (S)**	**JLC-I (C)**	**JLC-I (X)**	**NLC**	**VLEPP**	**CLIC**
L (10^{33}cm^{-2}s^{-1})	7	4	4	7	6	8	15	2 - 9
RF Freq (GHz)	1.3	3.0	2.8	5.7	11.4	11.4	14	30
Rep Rate (Hz)	10	50	50	100	150	180	300	1700
Bunches per RF pulse	800	125	55	72	90	90	1	1 - 4
N (10^{10})	5.15	2.9	1.30	1.0	0.63	0.65	20.	0.6
BPM Precision (μm)†	10.	10.	NA	NA	1.	1.	0.1	0.1
$\gamma\epsilon_x/\gamma\epsilon_y$ (10^{-8}m)	2000/100	1000/50	330/4.5	330/4.5	330/4.5	500/5	2000/7.5	180/20
β_x^*/β_y^* (mm)	25/2	22/0.8	10/0.1	10/0.1	10/0.1	10/0.1	100/0.1	2.2/.16
σ_{x0}/σ_{y0} (nm)	1000/64	670/28	300/3	260/3	260/3	300/3	2000/4	90/8
σ_L(μm)	1000	500	80	80	67	100	750	170
IP Crossing Angle (mrad)	0	3	7.3	8	7.2	3	--	1
Y	0.029	0.055	0.24	0.21	0.16	0.096	0.074	0.35
H_D	2.3	1.6	1.6	1.5	1.7	1.4	1.3	3.3
δ_B	0.03	0.03	0.10	0.08	0.05	0.03	0.13	0.36
n_γ	2.7	2.0	1.6	1.4	1.0	0.9	5.0	4.7
Loaded Grad. (MV/m)	25	17	19	33	31	38	96	78 - 73
Two Linac Length (km)	20	29.4	28	16.7	17.7	14	6.4	6.6
Section Length (m)	1.04	6	3.6	2	1.3	1.8	1.01	0.273
Number of Sections	19232	4900	7776	8360	13600	7778	5200	24000
Number of Klystrons	1202	2450	1944	4180	3400	1945	1300	2
Klystron Peak Power (MW)	3.25	150	85	45	70	94	150	700
Klystron Pulse Length (μs)	1300	2.8	4.5	3.6	0.84	1.5	0.7	0.011
Pulse Length to Section (μs)	1300	2.8	1.2	0.6	0.21	0.25	0.11	0.011
Pulse Compression Gain	--	--	2.4	4.2	3.2	4	4.22	--
a/λ (input/ output cavity)	0.15	.15/.11	0.13	.16/.12	.24/.14	.22/.15	.14	.2
P_B (MW)	16.5	7.3	1.4	2.9	3.4	4.2	2.4	.4 - 1.6
AC Power (MW)	137	114	106	193	86	141	91	175
$2P_B/P_{AC}$	0.24	0.13	0.03	0.04	0.09	0.06	0.05	0.02

† Addition to G. Loew's compilation (from Ref. 14).

particles per bunch spaced 16 nsec apart. The RF pulse has 420 J of energy; a single bunch extracts 0.95 J from the accelerator RF fields, and the bunch train extracts a total of 118 J leading to an efficiency, η_B, for converting RF to beam energy of $\eta_B = 0.28$. If only a single bunch was accelerated, the RF pulse could be shortened to 1 μsec, the accelerator filling time, but the efficiency would be low, $\eta_B = 0.006$. A major advantage of multiple bunches is that the cost of filling the accelerator with RF energy has been amortized over a large number of bunches.

Multiple bunches have implications for both the fundamental and higher modes. The energy spread of the beam must be small to minimize emittance blow-up from dispersive effects in the linac and to minimize chromatic aberrations in the final focus. The bunch train lengths are comparable to filling times, and the accelerator structure must be prefilled and the RF amplitude ramped so that each bunch gains the same energy.[15]

The bunches are closely spaced, and they interact through higher modes. The transverse modes can cause emittance blow-up that is in addition to that from the short range transverse wakefield. The interaction between bunches must be reduced by damping higher order modes or by detuning, varying cell dimensions to spread mode frequencies, leading to destructive interference between the deflections from different cells.[16] Detuning and damping may have to be combined to get adequate reduction of the long range wakefields.

VLEPP has a single, large bunch, 2×10^{11} particles, and that results in $\eta_B = 0.12$. The large bunch and relatively high RF frequency impose stringent tolerances on the linac for emittance preservation and require a novel final focus, the traveling focus, where a head-tail energy shift is introduced to shift the focal point during the collision and prevent enormous disruption. CLIC has parameters for between one and four bunches, and studies of energy compensation and transverse modes for four bunches are in progress.[17]

Present day, conventional linacs are modular with each module consisting of a modulator, klystron, possibly an RF pulse compression system, and, finally, one or more accelerator sections powered in parallel. The modulator converts AC power to high voltage, pulsed power. Most use a low voltage, lumped element transmission line for energy storage, thyratrons as switches, and a pulse transformer to step-up the output voltage. SLAC modulators are typical and are roughly 75% efficient.[18] A substantial fraction of the inefficiency comes from the rise- and fall-times of the pulse transformer. Improving modulator efficiency would be significant. A capacitor bank and high voltage switch tube rather than a pulse transformer was being considered for the SBLC, but has been given up for lack of an appropriate switch tube. A DC high voltage supply and girded klystron is being developed for VLEPP.

A short, high power RF pulse is the ideal for high frequencies because short sections and high group velocities are favored by efficiency and wakefields. The input power must be multiplied by $\tau^2/(1 - e^{-\tau})^2$ for the same average accelerating gradient ; $\tau \propto \zeta/(\lambda^{1.5}\beta_g)$ where ζ is the section length, β_g is the (normalized) group velocity, and λ is the RF wavelength.[19] The wavelength dependence comes from the skin effect. The maximum transverse wakefield behaves as $1/(a^3(\lambda/a)^{.8}))$ where a is the radius of the waveguide iris.[20] Increasing l/a reduces the wakefield with the side effect of raising the group velocity.[19]

It is impractical to generate short RF pulses directly. Modulator efficiency would be poor because pulse rise-and fall-times would be a large fraction of the pulse and klystron peak power would be enormous. Pulse compression[21] which raises the peak power while shortening the RF pulse is used for matching klystron capabilities to an optimum accelerator configuration and is a feature of the high RF frequency colliders.

TESLA has unique power source requirements. The high Q and long pulse length reduce the peak power to 3.25 MW, but the modulator must be capable of delivering that power for over a millisecond.

All except CLIC have a large number of klystrons. CLIC is a two-beam accelerator which replaces all of this with a single, low-energy beam traveling parallel to the high energy beam. This low-energy beam has a time structure appropriate for generating 30 GHz RF. It is accelerated by a superconducting RF system, and energy is extracted with transfer structures spaced roughly 1.5 m apart.

The vertical invariant emittances, $\gamma\varepsilon_y$, are small, and emittance preservation during acceleration is an important consideration. Emittance growth caused by the combination of injection jitter and wakefields must be controlled by tight tolerances on injection elements and BNS damping.[22] Those tolerances range from about 1 μm for NLC and JLC-I(X) to about 10 μm for the S-band accelerators and TESLA.[14]

Misalignments in the main linac cause emittance growth through wakefields and dispersion. With straight one-to-one orbit correction, i. e. steering to the middle of beam position monitors, there would be extremely tight tolerances on accelerator, quadrupole, and beam position monitor alignment. As examples, those tolerances would be about 10 μm for SBLC and half that for NLC.

Beam-based orbit correction procedures, where optical elements are varied and orbit changes measured, relieve these tolerances substantially.[14] The strengths of all the quadrupoles are increased, or decreased, in Dispersion Free (DF) steering to measure momentum dependence of the central trajectory; then, the orbit is corrected to minimize the dispersion. The strengths of focusing quadrupoles are reduced while those of defocusing quadrupoles are raised to approximate the defocusing effect of wakefields in Wakefield Free (WF) steering. Wakefield free steering requires good local alignment between quadrupoles and accelerator sections. Since these procedures depend on measuring orbit changes, the beam position monitors (BPM's) must be precise. Estimates of the required precisions are included in Table III and range from 0.1 μm for CLIC and VLEPP to 10 μm for SBLC and TESLA.[14]

The beams are flat at the interaction point to minimize backgrounds (see below) with $\gamma\varepsilon_x >> \gamma\varepsilon_y$ and $\beta_x{}^* >> \beta_y{}^* > \sigma_L$ (for all but VLEPP with its traveling focus) where σ_L is the bunch length. The vertical dimension is the most demanding with the vertical sizes before disruption ranging from 64 nm (TESLA) to 3 nm (JLC, NLC).

The vertical spot sizes quoted are the first order sizes, $\sigma_{y0} = (\beta_y{}^*\varepsilon_y)^{1/2}$, and up to third order geometric and chromatic aberrations must be corrected to reach those sizes. This is done by using dipoles to introduce dispersion in a region with sextupoles separated by a **-I** transformation. Synchrotron radiation losses in the chromatic correction section and in the final quadrupoles introduce important aberrations.

There are extremely tight pulse-to-pulse jitter tolerances. For all but the final doublet those tolerances are about $10\sigma_y$ while for the final doublet they are roughly σ_y.[23] The Final Focus Test Beam (FFTB) at SLAC will test many of the techniques for reducing aberrations to the required level and will provide a test bed for studying and specifying jitter tolerances.

The beams cross at an angle. This avoids unwanted collisions for colliders with closely spaced bunches, and it allows the channel for focusing the incoming beam to be independent of the channel for the exiting disrupted beam. Crab crossing,[24] tilting the bunches with an RF deflector, prevents luminosity loss due to incomplete overlap.

The luminosity is given by

$$L = \frac{N^2 f_c}{4\pi\sigma_{x0}\sigma_{y0}} H_D = \frac{N^2 f_c}{4\pi\sigma_x\sigma_y} ; \tag{4}$$

N is the number of particles/bunch and f_c is the collision frequency. Focusing during the collision, disruption, is accounted for by an enhancement factor, H_D, in the left-hand expression where the beams sizes without disruption are used, and by using the disrupted beam sizes in the right-hand expression.

The electromagnetic fields at the collision point are parametrized by[25]

$$Y = \frac{5r_e^2}{6\alpha} \frac{\gamma N}{\sigma_L(\sigma_x + \sigma_y)} . \tag{5}$$

Field enhancement due to disruption is accounted for approximately by using the disrupted sizes. This increases Y for TESLA, SBLC, and CLIC because the horizontal size is reduced about 50% by disruption in those cases. The mean energy beamstrahlung energy loss, $\delta_B \propto Y^2$, and backgrounds from beamstrahlung, e^+e^- pairs, and hadronic events depend on Y. When $Y \ll 1$ and $\sigma_x \gg \sigma_y$, the mean number of beamstrahlung photons per incident particle is[25]

$$n_\gamma \cong \frac{5\alpha^2\sigma_L}{2r_e\gamma} Y \cong \frac{2\alpha r_e N}{\sigma_x} . \tag{6}$$

This parameter serves as an approximate measure of backgrounds.

The luminosity can be rewritten in terms of only three free parameters: n_γ, σ_y, and the beam power, $P_B = N\gamma mc^2 f_c$,

$$L \cong \frac{1}{8\pi\alpha r_e mc^2} \frac{P_B n_\gamma}{\gamma\sigma_y} \tag{7}$$

The diversity of approaches in Table III arises from different judgments about the following.

The ease of developing new and improving existing technology - SBLC and JLC-I(S) are the most conservative in this regard. They take advantage of over forty years of experience with S-band RF. NLC, JLC-I(C), and JLC-I(X) extend the basis of present day linacs, high peak power klystrons and modulators, to higher frequencies. Klystrons and accelerator structures must be developed for those frequencies. TESLA relies on substantial improvements in the cost and accelerating gradient of superconducting RF. VLEPP requires innovations to meet demanding tolerances and relies on novel beam dynamics in the linac and final focus. CLIC has stringent tolerances because of its high frequency, and the RF power source development by itself is a major undertaking comparable to the complete development of other colliders.

Costs - Cost reduction and cost control must be dominant considerations as designs are developed. New technologies promise significant, but uncertain, cost reductions. Older technologies have better established costs, but these tend to be high and must be lowered through engineering and mass production. The experience of the SSC, an accelerator based on mature technology and a detailed design, teaches us that present linear collider cost estimates should not be taken seriously.

Extension to higher energies - An E_{CM} = 0.5 TeV collider should be a step towards multi-TeV energies. High gradients and high RF frequencies tend to be better for reaching high energies with room temperature RF. NLC, JLC-I(X), and VLEPP are optimized for 0.5 - 1 TeV while it would be difficult to directly extend S-band colliders beyond 0.5 - 1 TeV. CLIC is a multi-TeV collider scaled down to 0.5 TeV for purposes of comparison. The energy reach of TESLA depends on how close the fundamental gradient limit of ~50 MV/m in Nb can be approached. This issue of extension to higher energies is discussed more in the next section.

Experimental backgrounds and center-of-mass energy spread - The effects of beamstrahlung have been captured in eq. (7) with a single parameter, n_γ. This parameter doesn't account for the energy spectra of photons, e^+e^- pairs, and hadronic events, and it doesn't account for the overlap of events in the detector. The complicated interface between collider and experiment cannot be reduced to a single number, and it is only through the ongoing studies of that interface that tolerable background levels can be estimated.

Tolerances and beam power - The trade-off is given in eq. (7). Increasing the beam power relaxes injection tolerances, beam position monitor precision, and pulse-to-pulse jitter in the final focus by allowing a larger σ_y. However, there are limits to beam power from efficiency and beam handling, collimation and accelerator protection.

Prototypes addressing beam dynamics and engineering will help narrow the range of choices. These prototypes include:

1.- A 500 MeV TESLA prototype to be constructed at DESY to demonstrate a gradient of 15 MV/m, to meet cost goals, and to test a high gradient superconducting linac with beam.

2.- A 450 MeV SBLC prototype that will test long pulse, high power, multiple bunch operation of an S-band linac.

3.- The Accelerator Test Facility at KEK that combines a 1.5 GeV, S-band linac with a prototype damping ring. The damping ring will produce beams with brightness, single bunch charge, and bunch train structure covering many of the colliders in Table III. New levels of tolerances, control of beam generated fields, extraction kicker stability, etc. will be reached in accomplishing this.

4.- Interaction region optics and stability will be studied at the Final Focus Test Beam at SLAC. In addition, strong field QED, the regime of beamstrahlung in high energy linear colliders, will be explored experimentally.

5.- A 540 MeV prototype NLC linac has the goals of constructing, reliably operating, and studying beam dynamics in an X-band linac.

6.- A ~500 MeV VLEPP prototype will test the klystrons, accelerator, and beam dynamics of that collider.

7.- A beam with the time structure of the CLIC drive beam will be generated by an RF gun, accelerated and used for demonstrating energy extraction at the CLIC Test Facility.

The lessons learned from continuing operation of the SLC and the answers to some broader questions will contribute as much as or more than these prototypes to determining the best approach for the next generation linear collider.

THREE ISSUES FOR THE FUTURE

There has been a change in the considerations that have dominated linear collider parameters. Early on the possibility of large accelerating gradients made high RF frequencies, laser-driven grating accelerators, and plasma accelerators attractive. Energy efficiency and beam dynamics have become more important now as the beam requirements and operating costs have become better understood. Complexity is a major factor that is still not being given the attention required. An assumption underlying the range of parameters in Table III is that each of colliders would be equally operable. There is no reason to believe this.

For example, the number of klystrons for the conventional, room temperature colliders in Table III (SBLC, JLC-I, and NLC), ranges from 1944 to 4180. Each klystron and its associated modulator is a major piece of equipment The factor of two range in the number of klystrons has the potential of making the difference between a collider that can be commissioned rapidly and will run reliably, and one that will not. Of course, more than just the number of klystrons is involved in assessing reliability; the properties of the components themselves are as important. The principles of reliability engineering and Quality Assurance need to be used to estimate the required reliability and provide a scientific basis for judging operability. This should become a part of the discussion soon.

Attention is focused on $E_{CM} = 0.5$ TeV for the next collider. Reaching much higher energies is one of the aspirations of the linear collider community, and one reason for supporting a 0.5 TeV collider is that it could serve as an intermediate prototype for a higher energy collider. Therefore, it is important to understand how the various approaches extend to higher energy. There are two different questions.

First, can a particular collider reach higher energies? There are ideas for extending the energy of all of the colliders in Table III up to $E_{CM} \approx 1$ TeV. Table IV gives parameters for three of them. The energy is increased by either: 1) keeping the length the same and increasing the peak power to the linac by a factor of four thereby doubling the gradient; or 2) doubling the length of the linac. At 0.5 TeV the trade-off between beam power and spot size in eq. (7) was exploited by TESLA and SBLC to increase the vertical spot size by increasing the beam power. That trade-off is not nearly as dramatic at 1.0 TeV. Everyone is relying on small spots to make luminosity.

Second, can an approach be extended to substantially higher energies, say $E_{CM} = 2 - 5$ TeV? It isn't productive to write down parameters of a collider two generations beyond the SLC; too much will be learned between now and then. Trends are clear, however; low beam power and small spots is the direction needed for multi-TeV colliders. The two different approaches to building a 0.5 TeV, superconducting RF and room temperature RF, have different outlooks for 2 - 5 TeV.

The advantage of superconducting RF at $E_{CM} = 0.5$ TeV is the ability to trade-off beam power and spot size, but that advantage has largely gone away by 1 TeV. Superconducting RF is a low gradient technology. There is a fundamental limit of about 50 MeV/m that comes from the breakdown of superconductivity when the surface field exceeds the critical field, and the practicalities of fabricating cavities makes the 25 MeV/m gradient of TESLA an ambitious but reasonable goal. The only way to extend the energy is to extend the length. A packing factor of 70% is hoped for, and the $E_{CM} = 1$ TeV accelerator is close to 55 km long for an active length of 40 km. The superconducting approach is not likely to take one far beyond $E_{CM} = 0.5$ TeV.

There is a factor of ten in the RF frequencies of the room temperature colliders in Table III, but there are many considerations in common including: multiple bunch energy control and higher mode damping and detuning needed for multiple bunches; precision beam position monitors, alignment, and steering algorithms needed for emittance preservation; optical corrections and jitter control for producing nanometer size spots; high reliability, low cost, efficient modulators, and economic fabrication of accelerator sections. Room temperature colliders are pushing technology and beam dynamics in the directions needed for multi-TeV collisions. In addition, the room temperature RF approach does not have a fundamental gradient limit forcing one to

Table IV Comparison of Linear Collider Parameters for
$E_{CM} = 0.5$ TeV and $E_{CM} = 1.0$ TeV

Parameter	**TESLA**		**SBLC**		**NLC**	
E_{CM} (TeV)	0.5	1.0	0.5	1.0	0.5	1.0
L (10^{33}cm^{-2}s^{-1})	7	10	4	6	8	20
Rep Rate (Hz)	10	5	50	50	180	120
Bunches/RF pulse	800	4180	125	50	90	67
N (10^{10})	5.15	0.91	2.9	2.9	0.65	1.3
$\gamma\epsilon_x/\gamma\epsilon_y$ (10^{-8}m)	2000/100	520/6.3	1000/50	1000/10	500/5	500/5
β_x^*/β_y^* (mm)	25/2	20/1	22/0.8	32/0.8	10/0.1	40/0.1
σ_{x0}/σ_{y0} (nm)	1000/64	325/8	670/28	572/9	300/3	425/2
σ_L(μm)	1000	500	500	500	100	100
Y	0.029	0.058	0.055	0.091	0.096	0.28
H_D	2.3	2.0	1.6	1.7	1.4	1.6
δ_B	0.03	0.03	0.03	0. 07	0.03	0.08
n_γ	2.7	1.3	2.0	2.3	0.9	1.1
Load Grad.(MV/m)	25	25	17	34	38	76
Linac Length (km)	20	40	29.4	29.4	14	14
Number of Klystrons	1202	2404	2450	4900	1945	3890
Klystr Pk Pwr (MW)	3.25	3.25	150	150	94	188
Pulse Comp. Gain	--	--	--	2	4	4
P_B (MW)	16.5	15.2	7.3	5.8	4.2	8.0
AC Power (MW)	137	159	114	200	141	280
$2P_B/P_{AC}$	0.24	0.19	0.13	0.06	0.06	0.06

The $E_{CM} = 0.5$ TeV parameters are from G. Loew,[13] and the $E_{CM} = 1.0$ TeV parameters from B. Wiik.[26]

increase length to reach high energies. A room temperature, $E_{CM} = 0.5$ TeV collider has promise as an intermediate prototype for multi-TeV collisions.

There is world wide interest in building a large linear collider, and the interested parties have formed technical and scientific collaborations to that end. TESLA and the FFTB are two broad based, international collaborations pursuing linear collider development, and many of the other prototypes have participation outside of the home laboratory. The LC (Linear Collider) series of workshops has been a forum for accelerator physics discussions, and the workshops on Physics and Experiments at Linear Electron-Positron Colliders have played a similar role for the particle physics at these accelerators. A formal agreement on collaboration on accelerator development is being circulated, and the first collaboration council meeting should be in June, 1994.

A political mechanism for the support of a large linear collider is needed in addition to these scientist-to-scientist and laboratory-to-laboratory collaborations. Large fusion, space research, and high energy physics collaborations will set precedents for this. The former Director of the Office of Energy Research, William Happer, has commented on large scale high energy physics projects in the light of what is happening with ITER, the International Thermonuclear Experimental