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SUMMARY OF THE LINEAR COLLIDER WORKING GROUP*

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INTRODUCTION

The focus of the Linear Collider Working Group was on a next generation linear collider with the general parameters shown in Table 1. The energy range is dictated by physics with a mass reach well beyond LEP, although somewhat short of SSC. The luminosity is that required to obtain $10^3 - 10^4$ units of R_0 per year. The length is consistent with a site on Stanford land with collisions occurring on the SLAC site. The power was determined by economic considerations. Finally, the technology was limited by the desire to have a next generation linear collider before the next century.

Table 1. General parameters.

Energy	0.5 – 1.0 TeV in center-of-mass.
Luminosity	$10^{33} - 10^{34}$ cm^{-2} sec^{-1}.
Length	Each Linac $\lesssim$ 3 Km.
Power	$\lesssim$ 100 MW per Linac.
Technology	Must be realizable by 1990–92.

The basic configuration of such a linear collider is shown in Fig. 1. The beam is accelerated by an injector linac and then injected into a damping ring which damps the emittance of the beam and provides the beam with appropriate intensity and repetition rate. After extraction, the bunch must be compressed in length twice in order to achieve the short bunches suitable for the linac and final focus. The linac is used to accelerate the beams to high energy while maintaining the emittance. Finally, the final focus is used to focus the beams to a small spot for collision. This must yield a luminosity with tolerable beam-beam effects (disruption and beamstrahlung) and must also provide a reasonably background-free environment for the detector.

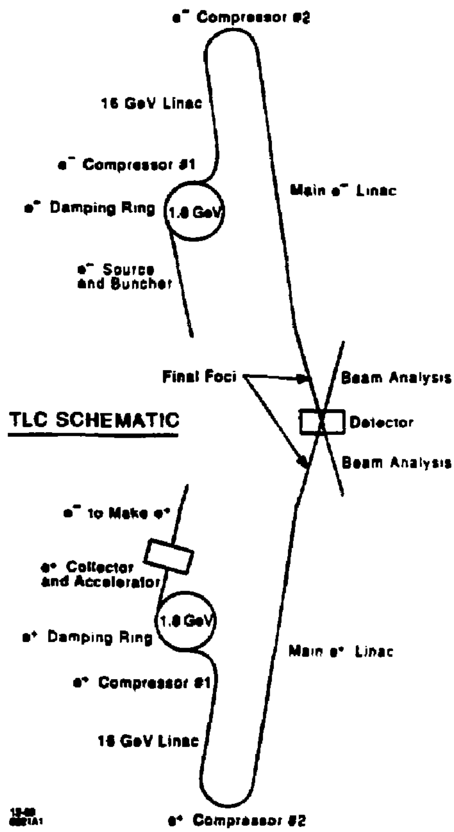

Fig. 1. Schematic layout of the TLC. The angles shown are exaggerated.

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Snowmass, Colorado, June 27–July 15, 1988.

Before launching into a rather detailed discussion of the contributions to the Linear Collider section of the Snowmass Proceedings, it is useful to discuss generally the overall results of the workshop and the months following. Perhaps one of the most important developments is the increased interest in an Intermediate Linear Collider (ILC) with an energy of 0.5 TeV in the center-of-mass. This is a factor of two below the TeV Linear Collider (TLC) and thus would require a factor of four less peak power provided that the machines were the same length. One can imagine designing an ILC which would be upgradable in energy by the addition of RF power and minor modifications to the final focus system.

If we begin the discussion of an ILC or TLC at the lower energy end, the damping ring and bunch compressor designs seem relatively straightforward with, however, somewhat tighter tolerances than usual. The main linac will probably have a structure similar to SLAC, except at 4–6 times the frequency. The irises will have slots coupled to radial waveguides to damp the transverse and longitudinal higher order modes. This makes possible the use of multiple bunches per RF fill, which increases the luminosity by a factor of 10 for "free."

There is no definite power source as yet. The recent demonstration of binary pulse compression at SLAC has focused attention on more conventional approaches to long-pulse power production. Low power, low loss tests of RF pulse compression are continuing at SLAC and initial results look very promising. There are plans to build a high power klystron at SLAC to feed the RF pulse compressor, and there are many new ideas for power sources which would drive RF pulse compressors. The relativistic klystron results have been somewhat discouraging, but much as been learned about the problems associated with these high current, high energy beams.

Once the power source problem is solved, we are still left with the luminosity problem. These two aspects are only partially decoupled due to the use of many bunches (a batch) per RF fill. To obtain the luminosity, we must preserve the emittance of the beam throughout the linac. This means tighter tolerances on vertical magnet alignment than are presently achieved. The final focus demagnifies the beam to obtain a very flat beam at the final focus. The chromatic correction for this is quite delicate, and tolerances are tight. Finally, we must measure the beam size at the interaction point in order to tune the final focus. Many of these problems can be addressed via a model final focus at a lower energy. Towards this end, there is presently work ongoing at SLAC to create a Final Focus Test Beam in order to test flat beam final focus optics, measurement techniques, alignment techniques, etc. This would use the 50 GeV SLC beam straight ahead into the old C-line at SLAC.

During the SLAC Workshop in December 1988, following Snowmass, there was one important discovery which should be mentioned here. Beamstrahlung photons create e^+e^- pairs upon interacting with the opposing bunch. One particle of the pair is deflected strongly by the field of the bunch. This, in turn, can cause serious background problems. P. Chen and B. Palmer discuss this in their papers.

Table 2. Linear collider working group participants

B. Ash—SLAC	R. Miller—SLAC
R. Blankenbecler—SLAC	A. Odian—SLAC
F. Bulos—SLAC	K. Oide—KEK/SLAC
D. Burke—SLAC	R. Palmer—BNL/SLAC
P. Chen—SLAC	E. Paterson—SLAC
Y. Chin—LBL	T. Raubenheimer—SLAC
B. Gabella—U. of Colo.	R. Ruth—SLAC
T. Himel—SLAC	K. Thompson—SLAC
S. Kheifets—SLAC	W. Vernon—UCSD
W. Kozanecki—SLAC	J. Wang—SLAC
N. Kroll—UCSD	B. Warnock—SLAC
G. Loew—SLAC	P. Wilson—SLAC
P. McIntyre—Texas A&M	

The list of working group participants is given in Table 2, while the Table of Contents gives a list of the contributions to the Proceedings. The purpose of the remainder of this paper is to provide guidance to the reader for the papers shown in the Table of Contents. To do this, I first discuss parameters briefly and then discuss damping rings. After discussing the basic concepts of bunch compression, I move to the contributions on linac structures and linac power sources. Since there is no specific paper on beam dynamics issues, in the next section I discuss emittance preservation in the linac in some detail. Next, the final focus papers are discussed and last, but not least, I introduce some of the issues for multibunch effects.

PARAMETERS

In this section, R. Palmer contributed a paper on linear collider energy scaling. Linear colliders are being considered for accelerators ranging from B-factories to Z-factories, up to a TeV Linear Collider. The purpose of this paper is to explore the change in the design of linear colliders as a function of energy given that one is always trying to maximize luminosity, but always respecting the limit on wall plug power shown in Table 1. A very wide range of energies is considered, and this leads to widely differing designs. In particular, one sees that the optimized RF frequency tends to decrease at lower energy while the repetition rate increases.

Table 3. Parameters for ILC and TLC.

		Low grad ILC	High grad ILC	TLC
General				
CM energy	TeV	.5	.5	1
luminosity 10^{33}	$cm^{-2}\ sec^{-1}$	1.5	2.9	6.2
RF wavelength	cm	1.75	1.75	1.75
repetition rate	kHz	.36	.36	.36
accel gradient	MV/m	93	186	186
number bunches		10	10	10
particles/bunch	10^{10}	.7	1.4	1.4
wall power	MW	52	103	210
length	Km	7.3	3.7	7.3
Damping				
emittance ϵ_x/ϵ_y		100	100	100
emittance $\gamma\epsilon_x$	μm	3.5	6.0	7.0
emittance $\gamma\epsilon_y$	m	.04	.04	.04
bunch spacing	m	.2	.2	.2
damping time	msec	2.1	2.3	2.3
RF				
pulse length	ns	60	60	60
peak power/length	MW/m	146	580	580
total RF energy	KJ	51	103	210
Linac				
loading η	%	2.5	2.5	2.5
iris radius a	mm	3.5	3.5	3.5
section length	m	1.6	1.6	1.6
Linac tolerances				
alignment	μm	20	35	30
vibration	μm	.009	.017	.012
Final focus				
β_y^*	mm	.1	.12	.11
crossing angle	mrad	4.2	6.1	3.8
disruption angle	mrad	.23	.31	.25
free length	m	.36	.43	.7
Intersection				
σ_y	nm	2.7	3.9	2.8
Oide min σ_y	nm	1.3	1.9	1.9
σ_x/σ_y		132	132	132
σ_z	μm	70	70	70
disruption D		5	5	5
lum enhance H		1.6	1.6	1.6
beamstrahlung δ	%	2	4	11
$\Delta p/p$ physics	%	.7	1.1	3.2

In addition, due to the interest in the ILC, Palmer considers two possible options for an ILC, both of which would be upgradable to a TLC with additional length/power sources. Perhaps the most attractive option is the low gradient ILC which has a physical layout identical to TLC but has one-half the acceleration gradient. The parameters for ILC and TLC are compared in Table 3.

There is also an addendum to Palmer's paper which discusses the problem of e^+e^- pair creation at the interaction point by beamstrahlung photons interacting with the oncoming bunch. He finds that by using his idea of 'crab crossing' it is possible to collide beams with a very large crossing angle. In this way, with the help of solenoidal guide fields, the deflected e^+ or e^- can exit through a large aperture hole adjacent to the incoming quadrupole. This means that the parameter sets which have been presented will have to be modified to include various changes, but the basic parameters still will be rather similar to those given in Table 2.

DAMPING RINGS

The paper by T. Raubenheimer, L. Rivkin and R. Ruth discusses many of the basic design considerations for the damping ring. The basic parameters of the TLC damping ring are shown in Table 4 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 $\epsilon_x/\epsilon_y = 100$. 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 threshold current refers to the threshold for the "microwave instability" or "turbulent bunch lengthening."

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 is necessary to decrease the damping time by the addition of wigglers in straight sections.

Table 4. Basic parameters of the SLC and TLC damping rings.

	TLC	SLC
Energy	$1 \sim 2$ GeV	1.15 Gev
Emittance, $\gamma\epsilon_x$	3.0 μmrad	36 μmrad
Emittance, $\gamma\epsilon_y$	30 nmrad	500 nmrad
Repetition rate	360 Hz	180 Hz
Bunch length	4 mm	5 mm[11]
Threshold Current	batches of 10 bunches of 2×10^{10}	1.5×10^{10} [11]

In Tables 5 and 6, you see the basic parameters for the ring. The lattice is combined function which allows the

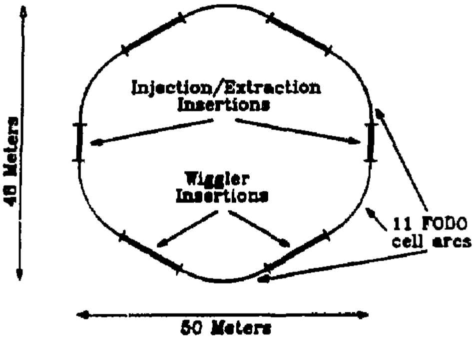

Fig. 2. Schematic of the TLC damping ring.

partition of the damping times to trade horizontal damping time for longitudinal. The RF frequency for this example is necessarily 1.4 GHz since the bunch spacing in this example is about 20 cm. The threshold impedance $(Z/n)_t$ is that for the microwave instability. It is quite small due to the small momentum compaction factor, but is only about a factor of three below that obtained in the SLC damping rings.

Table 5. TLC damping ring parameters.

Energy	$E_0 = 1.8$ GeV
Length	$L = 155.1$ meters
Momentum compaction	$\alpha = 0.00120$
Tunes	$\nu_x = 24.37, \quad \nu_y = 11.27$
RF frequency	$f_{RF} = 1.4$ GHz
Current	10 batches of 10 bunches of $2 \times 10^{10} e^+/e^-$

Table 6. TLC damping ring parameters.

	Wigglers Off	Wigglers On
Natural $\gamma\epsilon_x$	2.46 μmrad	2.00 μmrad
$\gamma\epsilon_x$ w/ intrabeam	3.33 μmrad	2.74 μmrad
Damping, τ_x	3.88 ms	2.50 ms
Damping, τ_y	9.19 ms	3.98 ms
Rep. rate, f_{rep}	155 Hz	360 Hz
Damp. partition, J_x	2.37	1.59
Energy spread, σ_ϵ	0.00128	0.00104
Radiation/turn, U_0	203 KeV	468 KeV
Bunch length, σ_z	5.6 mm	5.2 mm
Synch. tune, ν_s	0.0068	0.0058
$(Z/n)_t$	$\mathcal{F} \times 0.32\Omega$	$\mathcal{F} \times 0.20\Omega$
Natural chrom., ξ_x	-28.35	-28.07
Natural chrom., ξ_y	-25.10	-22.27

Another key aspect of the TLC design is the small vertical emittance. The design calls for an emittance ratio $\epsilon_x/\epsilon_y = 100$. This size emittance ratio is quite common in $e^\pm$ storage rings. However, the tolerances for obtaining such a small vertical beam size are proportional to this size. In the damping ring paper, those tolerances which are related to maintaining the emittance ratio are calculated. The tolerances presented in Sec. 5 of the paper are in the 100 μm range and could be improved by adding correction skew quadrupoles in the ring.

BUNCH COMPRESSION AND PRE-ACCELERATION

Designs for bunch compression are presented in a paper by S. Kheifets *et al.* In order to obtain the very short bunches necessary for the linac, it is necessary to perform at least two bunch compressions. A bunch length of about 50 μm in the linac puts a tight 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 energy spread $\Delta E/E = 10^{-3}$ and a bunch length of 5 mm, the two compressions are shown in Table 7. The first one decreases the bunch length by an order of magnitude. This is followed by a pre-acceleration section to decrease the relative energy spread in the beam by 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 current is as shown in Table 3, then the additional energy spread indu[illegible] about 5×10^{-4}. Neglecting this small increase [illegible] xt bunch compression happens at 18 GeV and se[illegible] reduce the bunch length to about 50 μm. This is suitable for injection into the high frequency, high gradient structure.

Table 7. Bunch compression.

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

The two designs shown in the paper by S. Kheifets *et al.* are for bunch compressors which have small bending angles. However, 180° bends which do the same job have also been designed.

LINAC

The linac is envisioned to be similar to the SLAC disk-loaded structure with a frequency at least four times the present SLAC frequency. The example shown in Table 3 is for six times the present SLAC frequency. The irises in the design are relatively larger 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 600 MW/m for the TLC or about 150 MW/m in the case of the ILC. In the case of the low gradient ILC, one can imagine an upgrade consisting of the addition of power sources.

Structures

The first paper on structures by G. Loew and J. Wang treats the question of RF breakdown. There have been many experiments done at various frequencies. If the scaling laws thus obtained are extrapolated to 11.4 and 17.1 GHz, the breakdown limited surface fields obtained are 660 and 807 MV/m, respectively. To convert this to effective accelerating gradient, a reduction factor of 2.5 is typically used.

In both cases, the accelerating gradient is above the 200 MeV/m used for the TLC design in Table 3. 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.

The next paper in the structures section is written by R. Palmer on Damped Accelerator Structures. 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. This paper 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 to do more detailed studies of slotted structures. The beam dynamics consequences of damping the higher modes is explored in the section on multibunch effects.

RF Power Sources

There are several papers contributed on the subject of RF power sources. The first and second paper are on the relativistic klystron and RF pulse compression, respectively. It is useful to contrast these approaches.

RF Pulse Compression

In Fig. 3(a), you see illustrated the basic principle of RF *pulse compression*. A long modulator pulse is converted by a high power, 'semi-conventional' klystron or some other power source into RF power with the same pulse width. This RF pulse is then compressed by cleverly slicing the pulse using phase shifts and 3 db hybrids and re-routing the portions through delay lines so that they add up at the end to a high peak power but for a small pulse width. This scheme was suggested by D. Farkas at SLAC and is presently under experimental investigation.[2] With a factor of 16 in pulse compression, the TLC would require a 50 MW klystron with a 1 μsec pulse length for each meter of the accelerator while the ILC would require a 50 MW klystron for each 4 meters of structure.

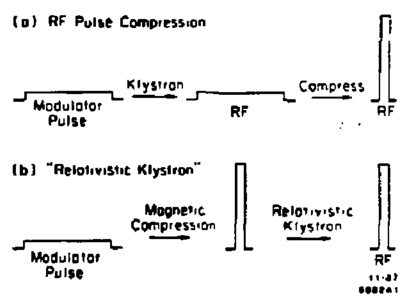

Fig. 3a. Illustration of RF pulse compression. 3b. Illustration of the relativistic klystron with magnetic compression.

The Relativistic Klystron

In Fig. 3(b), you see the principle of 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 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.

In the relativistic klystron paper by M. Allen *et al.*, four experiments are described. These are the result of a SLAC–LLNL–LBL collaboration which makes use of the

ARC facility (e^- beams 1.2 MeV and $\lesssim 1$ KA) at LLNL. Thus far the record peak power for any of the devices tested is 200 MW; however, in this case, the RF envelope was noticeably shortened. The highest power obtained with a wide RF pulse was about 80 MW. The most serious problem encountered in the experiment is the pulse shortening phenomenon; however, recent experiments suggest that this is caused by loading due to anomalous charged particle currents. A second serious problem is poor beam transmission. Finally, this RF power has been used to drive a 26-cm travelling wave structure at 11.4 GHz. The peak power of 200 MW corresponds to a local acceleration gradient of 140 MV/m. Work is continuing on this experiment.

In the second paper on RF pulse compression and alternative RF sources, P. Wilson describes RF pulse compression in some detail including estimates of efficiencies. There is an experimental test ongoing at SLAC which seeks to test a low loss, low power system. Initial results of this test have been very encouraging. A 100 MW, 11.4 GHz, "semi-conventional" klystron is presently being constructed at SLAC to perform high power tests of pulse compression. In the second section, the paper discusses other alternative RF sources for input to RF pulse compression.

The next paper on RF power, by W. Vernon, discusses another RF compression technique which uses RF energy storage combined with a high power switch to obtain very large compression of RF. This idea has been tested experimentally but needs much more work on high power switches to be feasible.

The next contribution on the cluster klystron, by R. Palmer and R. Miller, describes 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.

The final paper in this section on RF power is on the Gigatron by H. Bizek *et al.* This device makes use of the lasertron concept to produce a bunched beam directly at the cathode. Field emitting arrays are used for the cathode while a ribbon beam geometry is envisioned to control space charge effects. This device is another candidate for RF pulse compression and has an impressive efficiency on paper. Experimental tests are presently being prepared.

Emittance Preservation

There was no specific contribution to the Snowmass Proceedings on emittance preservation in the linac. The purpose of this section is to fill in that gap. The effects discussed are treated in more detail in Ref. 3.

Chromatic Effects

The filamentation of the central trajectory in a linac can cause dilution of the effective emittance of the beam. If we first consider a coherent betatron oscillation down the linac, then to be absolutely safe, we must require that it be small compared to the beam size. If the spread in betatron phase advance is not too large, then this tolerance is increased to perhaps twice the beam size for the cases shown in Table 3.

The chromatic effect of a corrected trajectory is rather different. In this case, it is the distance between an error and a corrector which matters, and the effects partially cancel yielding a growth $\propto \sqrt{N_{quad}}$. This yields a tolerance on magnet misalignment the order of 20 to 30 times the beam size in the linac (about 30 μm) for the cases shown in Table 3. This is also the tolerance on BPM measurements. If the phase advance of the linac or some subsection is not too large, then this yields a linear correlation of position with momentum (dispersion) which can, in principle, be corrected since it does not vary in time. Therefore, it may be possible to have looser tolerances if such correction is provided.

Transverse Wakefields and BNS Damping

The wakefield left by the head of a bunch of particles, if it is offset in the structure, deflects the tail. If the transverse oscillations of the head and tail have the same wave number, the tail is driven on resonance. This leads to growth of the tail of the bunch.[4] This effect can be controlled by a technique called BNS damping.[5] The bunch is given a head-to-tail energy correlation so that the tail is at lower energy. The offset of the head by an amount $\hat{x}$ induces a deflecting force on the tail away from the axis. The tail, however, feels an additional force $\Delta K \hat{x}$, where ΔK is the difference in focusing strength. These two forces can be arranged to cancel, thereby keeping the coherence of the bunch as a whole. For the designs shown in Table 3, the spread in energy for BNS damping is $\sim \pm.3\%$. This correlation can be accomplished by moving the bunch slightly on the RF wave to obtain a linear variation across the bunch.

Recently, BNS damping has been tested at the SLAC linac with great success. It is now part of normal operating procedure.

Jitter

In order to maintain collisions at the interaction point, the bunch must not move very much from pulse to pulse. Since the optics of the final focus also demagnify this jitter, the tolerance is always set by the local beam divergence compared to the variation of some angular kick. The jitter tolerance on the damping ring kicker is thus related to the divergence of the beam at that point. This is discussed in the paper on damping rings. At the injection point to the linac, the offset caused by this jitter must be small compared to the local beam size.

If all the quadrupoles in the linac are offset by random amounts, the effects accumulate down the linac and the orbit offset grows $\propto \sqrt{N_{quad}}$. This sets the tolerance on the random motion of quadrupoles to be much smaller than the beam size. In the examples in Table 3, the random jitter tolerances are $\simeq 0.01$ μm. On the other hand, tolerances for correlated effects are much less severe. In either case, this size motion from pulse-to-pulse is unlikely due to the large repetition rate of the collider. More gradual motion, which is larger, can be corrected with feedback.

Jitter in RF kicks can cause similar effects. These effects can be reduced by reducing the DC component of the RF kick. This is done by eliminating asymmetries in couplers and by careful alignment of structures.

Coupling

Finally, we discuss coupling of the horizontal and vertical emittance. The beam size ratio in the linac is 10:1. The tolerance on random rotations is given by

$$\Theta_{rms} << \frac{\sigma_y}{\sigma_x} \frac{1}{\sqrt{2N_q}} \quad .$$

For the examples shown in Table 3, the right-hand side is about 3 mrad. This seems quite straight forward. If the errors are not random, larger rotations can indeed result; however, because the beam size is so small, the effects are very linear. This means that skew quadrupoles can be used effectively as correction elements. Certainly in the final focus, skew quads will be an integral part of the tuning procedure to obtain flat beams.

FINAL FOCUS

The final focus, as described in the parameters in Table 3, 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 R. Palmer's paper, allows a much larger crossing angle than the diagonal angle of the bunch. As discussed in Palmer's contribution and in P. Chen's paper in this section, 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.

The first paper in this section by K. Oide treats the design of a flat-beam final focus. The vertical size is limited by the synchrotron radiation in the final quadrupole doublet coupled with the chromatic effect of a quad. He also shows how the system can be made much shorter and how the aperture of the final doublet can be increased. Finally, Oide discusses the pulse-to-pulse jitter tolerances on elements in the final focus. The most restrictive requirement 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 the next paper by W. Ash. In this paper, it is shown that passive vibration isolation seems to be more than adequate to handle the vibrations above $\sim$ 10 Hz at the high frequency end. For low frequencies, Ash suggests an interferometric feedback system to control motion to about 1 μm. Beam steering feedback can then be used to control slow variations in the 1 nm to 1 μm region.

A summary of beam-beam effects is presented by P. Chen. He begins by covering beamstrahlung and disruption for flat beams. The next subject is the kink instability induced if the beams are slightly offset vertically from each other. 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. The effect of this is to place restrictions on the product of the vertical and horizontal disruption per bunch. This effect is shielded somewhat if the quadrupoles are close to the interaction point. Chen concludes the main body of the paper with a discussion of *energy spectrum* and *maximum* disruption; issues which are important for final quad design and backgrounds.

The final section of Chen's paper is an addendum added after the SLAC Workshop in December 1988. As mentioned earlier in the Introduction, it was discovered that the beamstrahlung photons pair-produce in the coherent field of the bunch. The corresponding incoherent process has been known for some time, but its importance has only just been realized. 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. This leads to large angular kicks, as mentioned earlier in Palmer's paper on parameters. These stray particles can lead to more background problems, which must be addressed by further interaction point design. Some initial ideas were presented in Palmer's paper, but the problem needs much more study.

The discussion of beam-beam effects continues in a paper by R. Blankenbecler and S. Drell. They show how beamstrahlung photons can be used to create a photon-photon collider. They show an increase in luminosity for real photons *vs* virtual photons. At the time of Snowmass, the problem of pair creation had not been realized. This will probably not effect the luminosity results but would cause difficult background problems.

There is one final paper in the final focus section by T. Himel which deals with some of the background issues. He discusses background from synchrotron radiation in the final quad and also discusses the maximum disruption angle of an electron which has radiated most of its energy.

Clearly, with all this new information on the swarm of e^+e^- pairs produced, there needs to be much more study of the background problems, as well as interaction point geometry.

The measurement of the final spot size was not studied at the Snowmass workshop. This 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. There was some initial work done at the workshop in June 1988 in Capri, Italy which was also reported at the SLAC workshop.[6] In addition, preliminary results were presented at the SLAC workshop on the use of beamstrahlung from an ionized gas jet.[7] Although this looks promising, there is still much work to be done.

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. K. Thompson and R. Ruth have written a paper for this section which traces the problem of multibunches all the way through the linear collider, subsystem by subsystem. Damped accelerating cavities are required for the main linac and the damping rings. 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.[8] However, the benefits of multibunching seem to far outweigh any difficulties they impose due to the order of magnitude increase in luminosity.

OUTLOOK

A key result of the Snowmass Workshop is the increased interest in an ILC, that is, a linear collider with 0.5 TeV in the CM which might be upgradable to 1.0 TeV with additional power sources. Since there is a factor of four difference in peak power for the ILC and TLC (for a fixed length), the power source looks much easier to do. Designs of damping rings, bunch compressors and final focus systems are continuing. Perhaps the most important point was realized only after theSnowmass Workshop — beamstrahlung pair creation at the interaction point. The control of backgrounds in the face of pair creation needs much more work. However, with a sufficiently intensive R&D program towards power sources, final focus systems, etc. during the next few years, we may see a proposal for a next generation Linear Collider in the early 1990's.

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REFERENCES

1. L. Z. Rivkin *et al.*, "Bunch Lengthening in the SLC Damping Ring," SLAC-PUB-4645 (1988).
2. Z. D. Farkas, *IEEE Transcripts on Microwave Theory and Techniques*, **MTT-34**, No. 10 (1986) 1036, and also SLAC/AP-59.
3. R. D. Ruth, *Emittance Preservation in Linear Colliders*, in Lecture Notes in Physics, **296**, Frontiers of Particle Beams, Eds. M. Month, S. Turner, South Padre Island, Texas, 1986, and in SLAC-PUB-4436.
4. A. Chao, B. Richter and C. Yao, *Nucl. Instr. Meth.* **178**, 1 (1980).
5. V. Balakin, A. Novokhatsky and V. Smirnov, *Proceedings of the 12th International Conference on High Energy Accelerators*, Fermilab, (1983) p. 119.
6. J. Norem, presented at the *International Workshop on Next Generation Linear Colliders*, in preparation.
7. D. Burke, P. Chen, M. Hildreth and R. Ruth, work in progress.
8. R. D. Ruth, *Multi-Bunch Energy Compensation*, in proceedings of workshop on "Physics of Linear Colliders," Capri, Italy, 1988; and in SLAC-PUB-4541.

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