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PROGRESS ON NEXT GENERATION LINEAR COLLIDERS*

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1. INTRODUCTION

The purpose of this paper is to review progress in the U.S. towards a next generation linear collider. During 1988, there were three workshops held on linear colliders: 1.) "Physics of Linear Colliders," in Capri, Italy, June 14–18, 1988; 2.) Snowmass 88 (Linear Collider subsection) June 27–July 15, 1988; and 3.) SLAC International Workshop on Next Generation Linear Colliders, Nov. 28–Dec. 9, 1988. To obtain detailed current information, the reader is directed to Refs. 1-3 which are the proceedings of each of the workshops. In addition, the Snowmass proceedings for the linear collider working group are collected in Ref. 4. This paper will concentrate on U.S. efforts and will draw heavily from Refs. 3 and 4.

There is also much work ongoing in other parts of the world. The Soviet Union is planning a linear collider at Serpukov which is being designed at Novosibirsk. CERN is working on CLIC (CERN Linear Collider). Finally, KEK is actively engaged in linear collider research towards a JLC (Japanese Linear Collider). Much of this work is covered in Refs. 1 and 3.

In this paper, I focus on reviewing the issues and progress 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.

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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.

Before proceeding to a detailed discussion of the linear collider subsystem by subsystem, it is useful to discuss generally the overall results of the past year's activities. 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

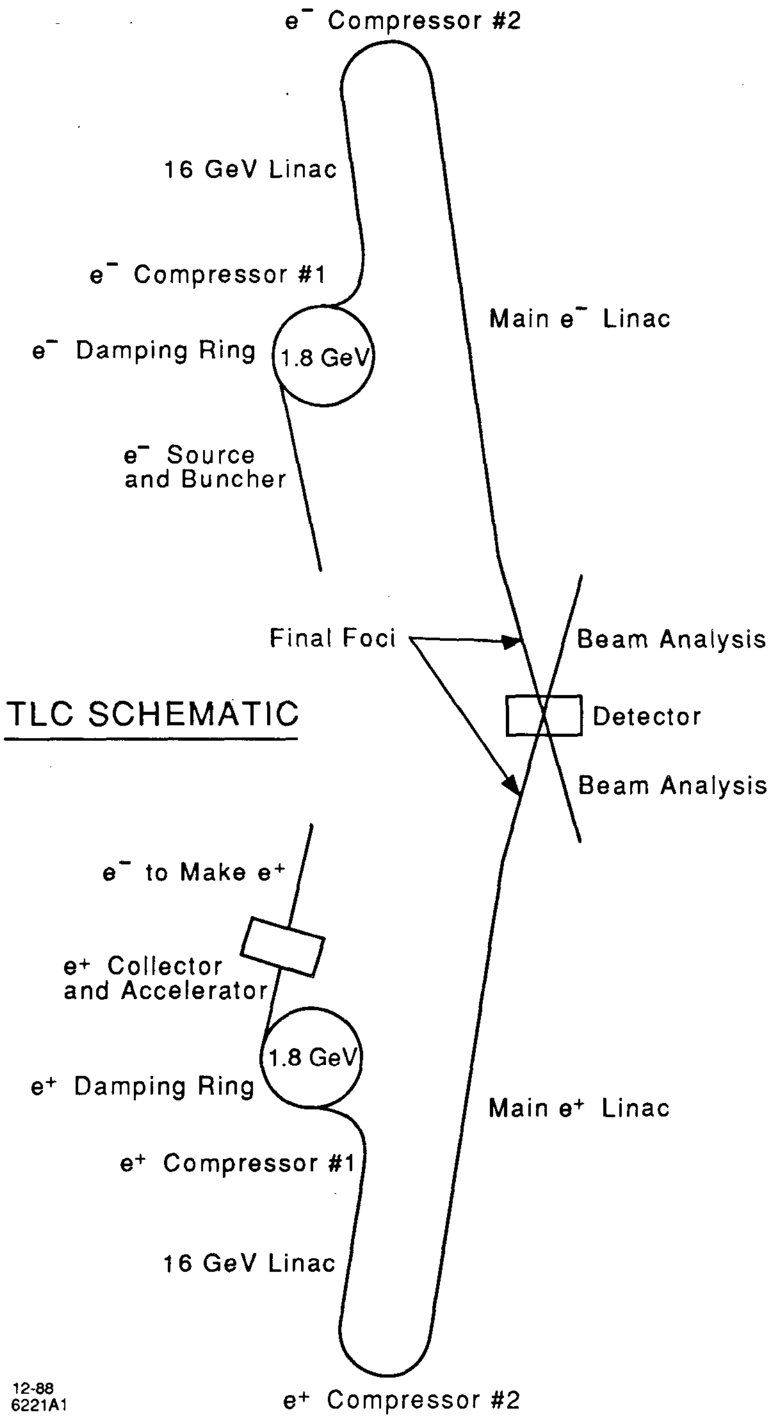

Fig. 1. Schematic layout of the TLC. The angles shown are exaggerated.

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 emphasized 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. This will be discussed more thoroughly in the later sections of this paper.

In the next sections, I first discuss parameters briefly and then discuss damping rings. The basic principles of bunch compression are treated in the next section. In the section on the linac, there are three subsections. First I discuss RF structures and power sources, and then I move to a discussion of emittance preservation in the linac. This is followed by a discussion of the final focus and beam-beam effects. Finally, I introduce some of the issues for multibunch effects.

2. PARAMETERS

Linear colliders are being considered for accelerators ranging from B-factories to Z-factories, up to a TeV Linear Collider. In Ref. 5, R. Palmer explores 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.

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 2.[5]

There is also an addendum to Ref. 5 which discusses the problem of e^+e^- pair creation at the interaction point by beamstrahlung photons interacting with the oncoming bunch. Palmer 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

Table 2. Parameters for TLC and ILC.

		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 Ring				
emittance ϵ_x/ϵ_y		100	100	100
emittance $\gamma\epsilon_x$	μm	3.5	6.0	7.0
emittance $\gamma\epsilon_z$	m	.04	.04	.04
bunch spacing	m	.2	.2	.2
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
free length	m	.36	.43	.7
Intersection				
σ_y	nm	2.7	3.9	2.8
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
Δp/p physics	%	.7	1.1	3.2

shown here will have to be modified somewhat to include various changes, but the basic parameters still will be rather similar to those given in Table 2.

3. DAMPING RINGS

In Ref. 6, T. Raubenheimer *et al.* discuss many of the basic design considerations for the damping ring. The basic parameters of the TLC damping ring are shown in Table 3 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 3. 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[7]
Threshold Current	batches of 10 bunches of 2×10^{10}	1.5×10^{10} [7]

In Tables 4 and 5, you see the basic parameters for the ring. The lattice is combined function which allows the 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.

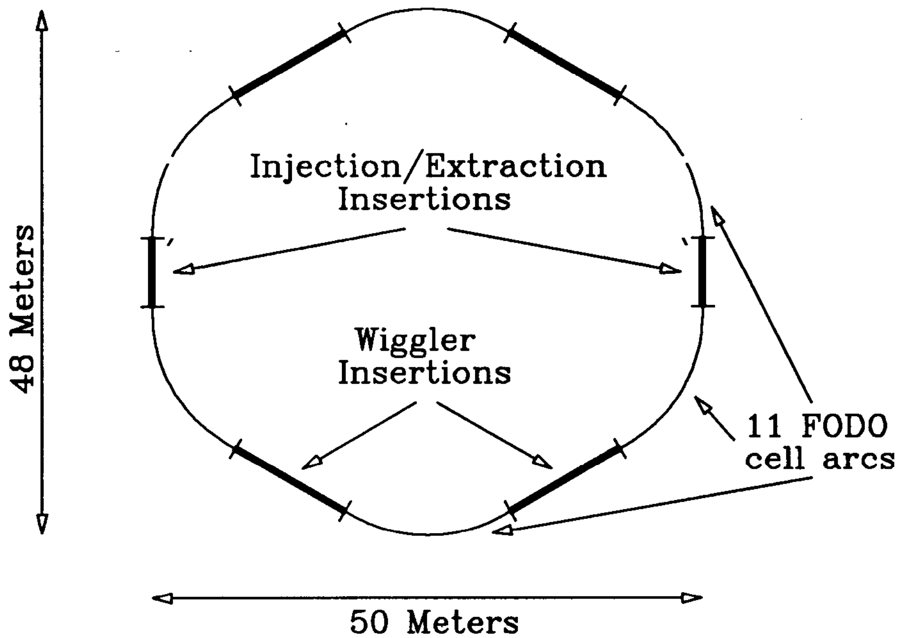

Fig. 2. Schematic of the TLC damping ring

Table 4. 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 $2 \times 10^{10} e^+/e^-$

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 Ref. 6 , 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.

Table 5. 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

4. BUNCH COMPRESSION AND PRE-ACCELERATION

In order to obtain the very short bunches necessary for the linac, it is necessary to perform at least two bunch compressions after the damping ring. Designs for bunch compression are presented in Ref. 8. 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 6. 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 2, then the additional energy spread induced is about 5×10^{-4}. Neglecting this small increase, the next bunch compression happens at 18 GeV and serves to reduce the bunch length to about 50 μm. This is suitable for injection into the high frequency, high gradient structure.

The two designs shown in Ref. 8 are for bunch compressors which have small bending angles. However, 180° bends which do the same job have also been designed.

Table 6. 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

5. 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 2 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. This section is divided into three subsections. In the first subsection we discuss structures, the second deals with RF power sources, and finally the third treats emittance preservation in the linac.

5.1 STRUCTURES

Since the gradients range from 100 MV/m to 200 MV/m, the first question that arises is RF breakdown. This question is treated in Ref. 9. In this paper G. Loew and J. Wang present results from many experiments 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 2. However, the measurements also indicated significant "dark currents" generated by captured field-emitted electrons. The question of the effects of dark current on loading and beam dynamics is not yet resolved and needs further study.

As mentioned in the Introduction, in order to make efficient use of the RF power and to achieve high luminosity, it seems essential to accelerate a train of bunches with each fill of the RF structure. This leads to two problems: (1) the energy of the bunches in the train must be controlled and (2) the transverse stability of the bunch train must be ensured. Both of these problems are helped greatly by damping higher modes (both transverse and longitudinal) in the RF structure. In Ref. 10, R. Palmer describes a technique of using slotted irises coupled to radial waveguides to damp these modes: Q's as low as 10–20 have been measured in model structures. This encouraging evidence has led to a development program at SLAC 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.

5.2 RF Power Sources

Before discussing results on power sources, it is useful to contrast and compare two basic approaches, RF pulse compression and the relativistic klystron.

5.2.1 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 invented by D. Farkas at SLAC and is presently under experimental investigation.[11] With a factor of 16 in pulse compression, the TLC would require an 50 MW klystron with a 1 μsec pulse length for each meter of the accelerator while the ILC would require an 50 MW klystron for each four meters of structure.

In Ref. 12, 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.

5.2.2 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.

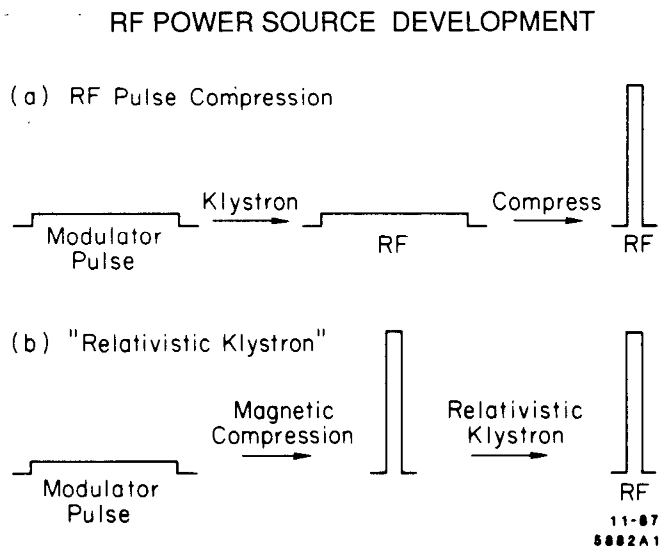

Fig. 3a. Illustration of RF pulse compression. 3b. Illustration of the relativistic klystron with magnetic compression.

In Ref. 13, four experiments on relativistic klystrons 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; 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.

Another interesting possible RF source is the cluster klystron. In Ref. 14, R. Palmer and R. Miller describe a multiple beam array of "klystrinos" which when coupled together can give impressive results. By dividing a single beam into many beams shielded from each other, the problems of space charge are effectively eliminated. This source could be used as a driver for RF pulse compression. Alternatively, with the addition of a grid and an oil-filled transmission line for energy storage, the device could directly produce short RF pulses. Thus far, there has been no experimentation; but calculations and cost estimates are encouraging.

Rather than separating the beam into separate beams, it is also possible to consider ribbon beam geometries. One possibility, the Gigatron, is presented in

Ref. 15. 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.

To conclude this section, it seems that if high power tests of RF pulse compression show positive results, there are several candidates to provide the long pulse input RF. Such an RF source combined with RF pulse compression would be a possible power source for an ILC or TLC which could be realized in the near future. All other possibilities seem somewhat more remote and need much more R&D.

5.3 Emittance Preservation

During the process of acceleration, we must take care not to dilute the emittance of the beam. There are several effects which can lead to emittance dilution. In the next few subsections, we discuss a few of the most important effects.

5.3.1 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 2.

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 in Table 2. 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.

5.3.2 *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.[16] This effect can be controlled by a technique called BNS damping.[17] 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 2, 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.

5.3.3 *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 Ref. 6. 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 vibrating in a random way, 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 2, the random jitter tolerances are $\simeq 0.01\ \mu$m. On the other hand, tolerances for correlated effects are an order of magnitude 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 by eliminating asymmetries in couplers and by careful alignment of structures.

5.3.4 *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 for a flat beam is given by

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

For the examples shown in Table 2, 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.

6. FINAL FOCUS

The final focus, as described in the parameters in Table 2, is a flat beam final focus with a crossing angle. The purpose of the flat beam is to increase the luminosity while controlling beamstrahlung and disruption. The crossing angle is to allow different size apertures for the incoming and outgoing beam. Another invention, "crab-wise crossing", discussed in Ref. 5, allows a much larger crossing angle than the diagonal angle of the bunch. As discussed in Ref. 5 and in Ref. 18, 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.

6.1 Final Focus Optics and Tolerances

The first job in the final focus is to demagnify the beam to provide a small spot for collision. The design for such a system is presented in Ref. 19 by K. Oide. This is a flat beam final focus which achieves the parameters shown in Table 2 for vertical and horizontal beam size. The vertical size is limited by a fundamental constraint "the Oide limit" due to the synchrotron radiation in the final doublet coupled to the chromatic effect of a quadrupole. The quadrupole gradients necessary are very high and in Oide's design are obtained by conventional iron magnets with 1 mm pole-to-pole distance. Tolerances are very tight in such a final focus. The most restrictive vibration tolerance is on the final doublet which must be stable pulse-to-pulse to about 1 nm.

Since vibration of the final doublet is the most serious problem, it is considered in some detail in Ref. 20. In this paper, it is shown that passive vibration isolation seems to be more than adequate to handle the vibrations above 10 Hz at the high frequency end. For low frequencies, W. 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.

6.2 Beam-Beam Effects

When a small bunch of electrons collides with a small bunch of positrons, the fields of one bunch focus the other causing disruption. Since the opposing particles are strongly bent, they also emit radiation called beamstrahlung. These are the two basic beam-beam effects. The disruption enhances the luminosity by a small amount while the beamstrahlung causes significant energy loss during collision and increases the effective momentum spread for physics. (See Table 2.) These issues are discussed in more detail in Ref. 18.

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

The final section of Ref. 18 is an addendum added after the SLAC Workshop in Dec. 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.[21] 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 Section 2.

These stray particles can lead to more background problems, which must be addressed by further interaction point design. In Ref. 5, it is suggested that crab-crossing combined with large crossing angles and solenoidal fields would allow one to channel these electrons out through a large exit hole to a beam dump. This idea looks promising but needs much more study.

The measurement of the final spot size is an extremely important, but as yet unsolved, problem. From SLC experience, it is probably possible to use beam-beam effects to minimize spot sizes. However, for the initial tune-up of the final focus, a single-beam method is almost essential. There was some initial work done at the workshop in June 1988 in Capri, Italy which was also reported at the SLAC workshop.[22] In addition, preliminary results were presented at the SLAC workshop on the use of beamstrahlung from an ionized gas jet.[23] Although this looks promising, there is still much work to be done.

7. MULTIBUNCH EFFECTS

As mentioned earlier, in order to efficiently extract energy from the RF to obtain high luminosity, it is essential to have many bunches per RF fill. This, however, leads to transverse beam breakup. The invention of damped structures discussed in Section 5.1 helps but does not completely solve the problem for the linac. It is also necessary to tune the frequency of the first dipole mode of the accelerating structure. This is discussed in Ref. 24 where the problem of multibunching is traced all the way through the linear collider subsystem by subsystem. Damped accelerating cavities are required for the main linac and the damping rings, while other systems can get by with very strong focusing. Thus, from the transverse point of view, stability seems possible.

In addition, it is necessary to control the energy spread from bunch to bunch very precisely ($\Delta E/E \lesssim 10^{-3}$). This can be accomplished by injecting the bunches before the RF structure is full to match the extraction of energy by the bunches to the incoming energy as the structure fills. This leads to tight tolerances on phase and amplitude of the RF, as well as tight control of the pulse-to-pulse number of particles in a batch of bunches.[25] However, the benefits of multibunching seem to far outweigh any difficulties they impose due to the order of magnitude increase in luminosity.

8. OUTLOOK

During the past few years, there has been tremendous progress towards a next generation linear collider. We now have a much clearer picture of how to obtain both the energy and luminosity required. An important development this past year was the increased interest in an ILC, that is, a linear collider with 0.5 TeV in the CM which would be upgradable to 1.0 TeV with additional power sources. Since there is a factor of four difference in the peak power required for the ILC *vs.* the TLC, the initial power source looks much easier to do. We will probably see the development of a power source and structure during the next couple of years. This would yield the energy of the collider; what about the luminosity?

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

One key aspect of all linear collider design is background control. With the discovery of the swarm of e^+e^- pairs produced at the interaction point, there now needs to be detailed study of interaction point design to control backgrounds.

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

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