PROSPECTS FOR NEXT-GENERATION
e^+e^- 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 dolliders: 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 INP in 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 by 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.

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 few 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. From Fig. 1 an ILC could be upgradable in energy either by the addition of power sources or by increasing the linac length. The trombone shape lends itself well to increases in length.

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,
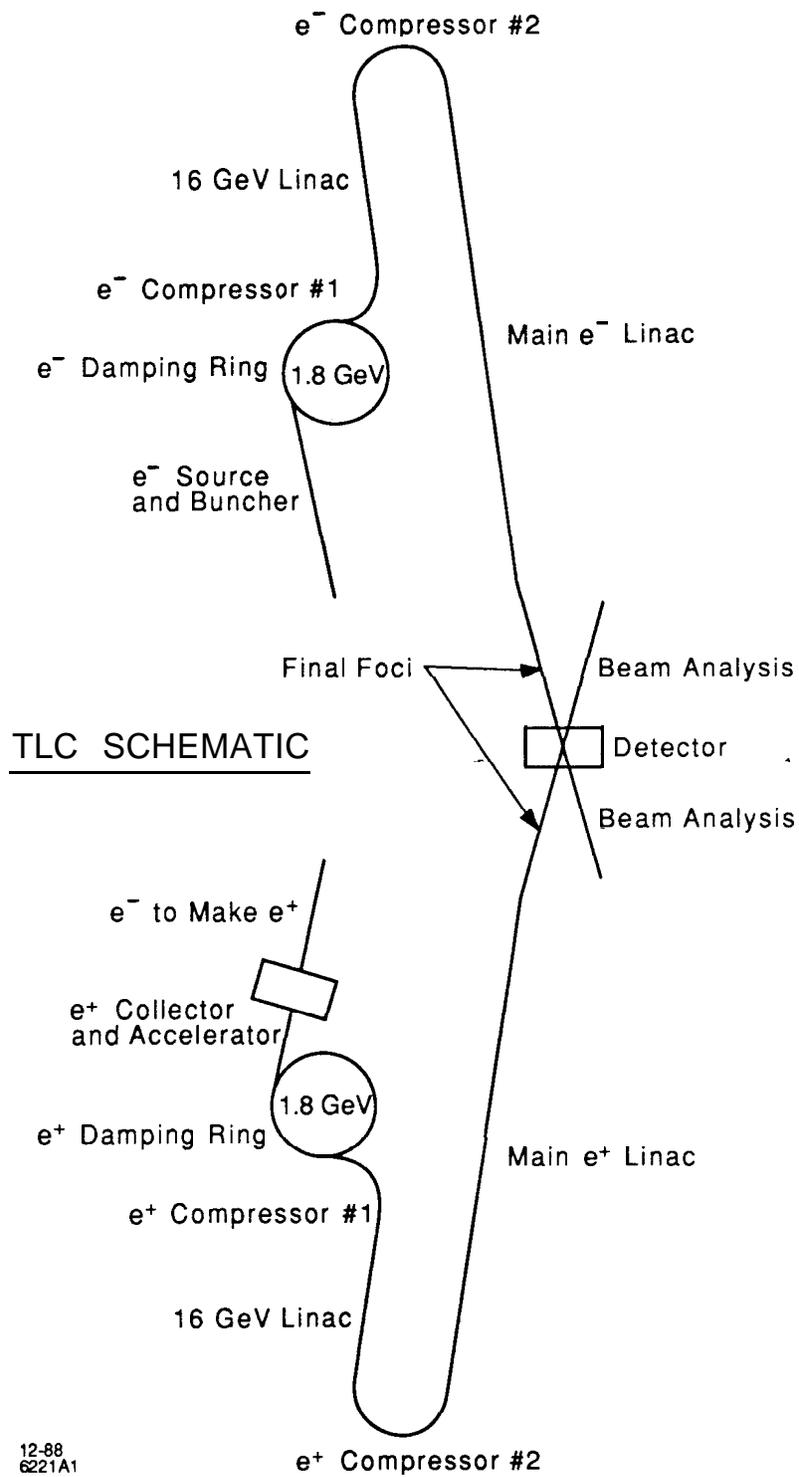
e⁻ Compressor #2

16 GeV Linac

e⁻ Compressor #1

e⁻ Damping Ring (1.8 GeV)

Main e⁻ Linac

e⁻ Source
and Buncher

Final Foci

Beam Analysis

TLC SCHEMATIC

Detector

Beam Analysis

e⁻ to Make e⁺

e⁺ Collector
and Accelerator

1.8 GeV

e⁺ Damping Ring

Main e⁺ Linac

e⁺ Compressor #1

16 GeV Linac

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e⁺ Compressor #2

Fig. 1. Schematic layout of an ILC or TLC. The angles shown are exaggerated.

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however, somewhat tighter tolerances than usual. The main linac will probably have a structure similar to SLAC, except at 4 times the frequency. The structure will be modified with holes coupled to waveguides in order 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. A high-power klystron is under construction at SLAC to feed the RF pulse compressor, and there are many new ideas for power sources which would drive RF pulse compressors.

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. 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, a Final Focus Test Beam is being constructed at SLAC by an international collaboration of SLAC, INP, KEK, and Orsay.

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

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effects. Finally, I introduce some of the issues for multibunch effects.

2. PARAMETERS

The parameters for a next-generation linear collider are far from being fixed. However, initial studies have yielded global parameters in the neighborhood of those presented in Table 2.[5] The parameters shown are for an ILC with 0.5 TeV in the CM. To upgrade to a TLC with 1.0 TeV in the CM one can either increase the RF power by a factor of 4 or increase the length by a factor of 2. With the higher energy beams, the spot sizes will decrease, and the beamstrahlung energy loss increases to the level $\sim$ 20%.

The interaction point geometry is given with two options: no crab crossing means that the crossing angle is within the diagonal angle of the bunch, crab crossing allows a larger angle by giving the beams a time varying transverse kick which causes the beams to overlap almost completely when they cross.

In the next several sections we discuss many of the issues which are input into the design of a linear collider such as that presented in Table 2.

3. DAMPING RINGS

In Refs. 6 and 7, T. Raubenheimer *et* al. discuss many of the basic design considerations for the damping ring. The basic parameters 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 ϵ_x/ϵ_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."

Table 2. Parameters for an ILC.

		ILC
General		
CM energy	TeV	.5
luminosity 10^{33}	cm -2 sec -1	3.9
RF frequency	GHz	11.4
repetition rate	Hz	360
accel gradient	MV/m	93
number bunches		10
particles/bunch (at IP)	10^{10}	1.6
length	Km	7.2
Damping Ring		
emittance ϵ_x/ϵ_y		100
emittance $\gamma\epsilon_x$	μm	3.5
emittance $\gamma\epsilon_z$	m	.04
bunch spacing	m	.21
Linac RF		
loading η	%	2.5
iris radius a	mm	4.6
section length	m	1.5
v_g/c		0.06
pulse length	ns	82
peak power/length	MW/m	194
Final focus		
β_y^*	mm	.08
crossing angle (no crab)	mrad	4.8
crab crossing angle	mrad	30-100
free length	m	.52
Intersection		
σ_y	nm	3.1
σ_x/σ_y		180
σ_z	μm	70
disruption D_y		10
lum enhance H		1.5
beamstrahlung δ	%	6

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

Table 3. Basic parameters of the SLC and TLC damping rings.

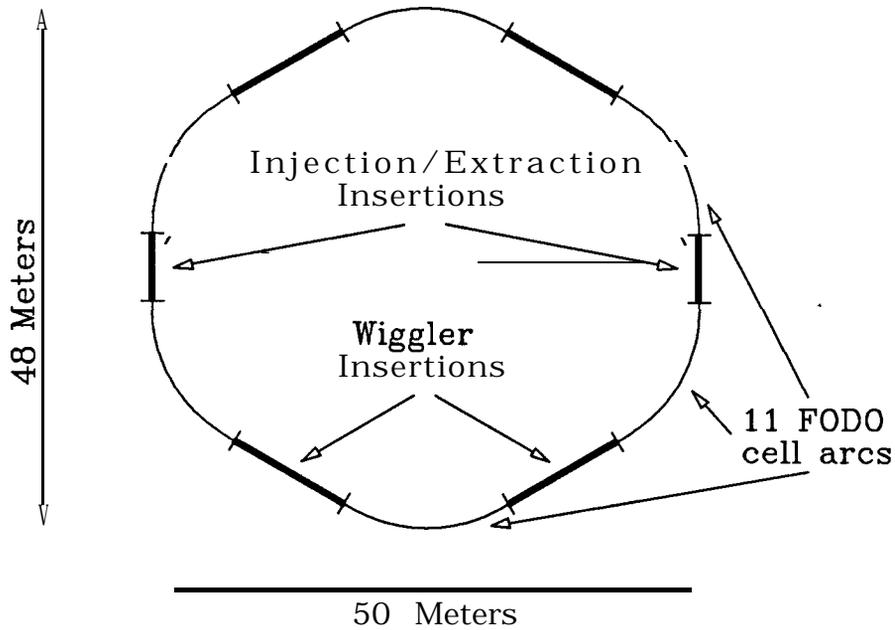|	TLC	SLC
Energy	1 ~ 2 GeV	1.15 Gev
Emittance, $\gamma\epsilon_x$	13.0 μmrad	36 μmrad
Emittance, $\gamma\epsilon_y$	30 nmrad	500 nmrad
Repetition rate	360 Hz	180 Hz
Bunch length	4 mm	5 mm
Threshold Current	batches of 10 bunches of 2 x 10^{10}	1.5 x 10^{10}

Fig. 2. Schematic of the TLC damping ring

wigglers in straight sections.

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

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

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

below that obtained in the SLC damping rings.

Another key aspect of the 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 a small vertical beam size are proportional to the absolute size. In Ref. 6 , those tolerances which are related to maintaining the emittance ratio are calculated. The tolerances presented in Sec. 5 of Ref. 6 are in the 100 μm range and could be improved by adding correction skew quadrupoles in the ring.

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. 9 and 10. A bunch length of about 50 μm in the linac puts a 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 about 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 x 10^{-4}. Neglecting this small increase, the next bunch compression happens around 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.

Table 6. Bunch compression.

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

The two designs shown in Ref. 9 are for bunch compressors which have small bending angles. Reference 10 presents several designs in which the bend angle for

the final compressor is $180°$ as shown in Fig. 1. This low energy bend allows easy upgrades in energy, and also makes it possible to do direct feedback to compensate jitter from the damping ring kicker magnet.

5. LINAC

The linac is envisioned to be similar to the SLAC disk-loaded structure with a frequency of four 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 900 $\mathrm{MW/m}$ for a 200 $\mathrm{MeV/m}$ TLC or about 220 $\mathrm{MW/m}$ in the case of a 100 $\mathrm{MeV/m}$ ILC.

The remainder of 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 being considered range from 100 $\mathrm{MV/m}$ to 200 $\mathrm{MV/m}$, the first question that arises is RF breakdown. This question is treated in Refs. 11 and 12. 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 $\mathrm{MV/m}$, 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 200 MeV/m. 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. 13, 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 and KEK 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 magnetic pulse compression.

5.2.1   RF Pulse Compression and Conventional Klystrons

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.[14] With a factor of 8 in pulse compression, a 100 MW klystron could power about 3 m of structure to achieve 100 MV/m.

In Ref. 15, P. Wilson describes RF pulse compression in some detail including estimates of efficiencies. An experimental test at SLAC of a low-loss, low-power system has been completed which yielded a factor of 3.2 power gain.[16] A 100 MW, 11.4 GHz "conventional" klystron, which has just been completed at SLAC, will be used to perform high-power tests of a pulse compression system designed to yield a power gain of 6.

(a) RF Pulse Compression

Klystron   Compress

Modulator Pulse   RF   RF

(b) "Relativistic Klystron"

Magnetic Compression   Relativistic Klystron

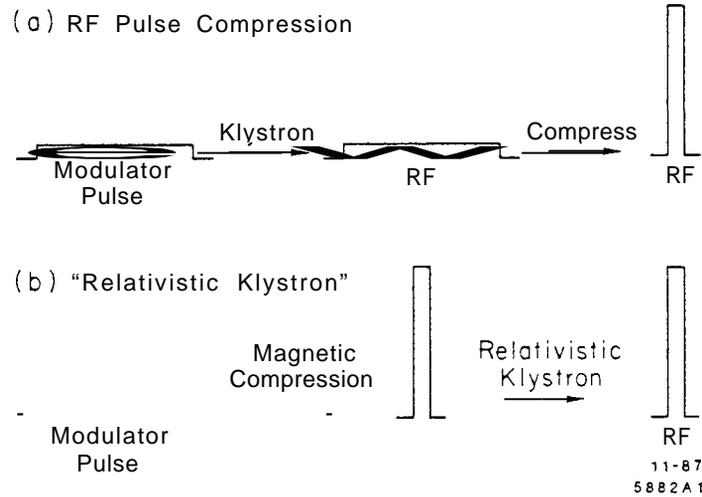Modulator Pulse   RF

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

5.2.2 *Magnetic* Pulse *Compression* and the Relativistic *Klystron*

In Fig. 3(b), you see the principle of magnetic pulse compression and 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 and then 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.

Experiments on the relativistic klystron are described in Ref. 17. The best power output achieved to date is 330 MW. Although higher acceleration gradients have been achieved, the best break-down free acceleration gradient in this experiment is 84 MV/m with 80 MW of RF power input into a 30 cm long accelerator

structure.

5.2.3   Other RF Sources

It is also possible to consider other sources driven by magnetic pulse compressors which directly produce short, high-power RF pulses. One example is a cross-field amplifier (CFA). This device has the geometry of a magnitron but is configured as an amplifier rather than an oscillator. SLAC is presently completing the construction of a 100 MW CFA which will be tested in early 1990. This device could also produce long RF pulses for RF pulse compression. Although it is a large extrapolation from existing sources, it holds the promise of being much cheaper than an equivalent power klystron.

Another interesting possible RF source is the cluster klystron. In Ref. 18, 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. 19. 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.

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 case 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 20 μm) for the case 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.[20] This effect can be controlled by a technique called BNS damping.[21] 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 AK 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 much less than 1%. 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 SLC with great success.[22] 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 $\simeq 0.01$ μm. 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 example shown in Table 2, the right-hand side is about 3 mrad; this is straightforward to achieve. 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. FINALFOCUS

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. 23, 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. 24 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. 25. 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, an interferometric feedback system can be used 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. These issues are discussed in more detail in Ref. 23.

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 when the disruption is not too severe. 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. 23 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.[26-29] The corresponding incoherent process has been known for some time, but its

importance has only just been realized.[30] T he 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. Further studies of this option have indicated that crossing angles in the range 30-100 mrad would be necessary to avoid particle impact in the detector.[31]

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.[32] In addition, preliminary results were presented'at the SLAC workshop on the use of beamstrahlung from an ionized gas jet.[33] Recently, there have been studies on the detection of the ions from a gas jet after beam passage.[34]

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.[35] In Ref. 36 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.[37] 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 or length. 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 SLC 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) and is being supported as a collaborative effort of SLAC, INP, KEK, and Orsay.

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. This effort is underway at SLAC and KEK.

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 detailed conceptual design in the early 1990's.

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