SLAC-PUB-4975
May 1989
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REPORT ON THE INTERNATIONAL WORKSHOP ON NEXT GENERATION LINEAR COLLIDERS*

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1. INTRODUCTION

Many laboratories around the world have begun vigorous research programs on a next generation linear collider (NLC). However, it has been recognized that the research towards NLC is beyond the capabilities of any one laboratory presently. This workshop was organized to begin a series of workshops that address this problem. Specifically, the main goals of the workshop were to discuss research programs of the various laboratories around the world, to identify common areas of interest in the various NLC designs, and finally to advance these programs by collaboration.

Table 1. Chairmen of Working Groups

Topic	Chairman	Scientific Secretary
Parameters	J. Rees	T. Mattison
RF Power	M. Allen	T. Lavine
Structures	G. Loew	J. Wang
Final Focus	D. Burke	T. Fieguth
Beam Dynamics	R. Ruth	K. Thompson
Damping Rings	L. Rivkin	T. Raubenheimer
Instrumentation	J. Seeman	G. Fischer

The workshop was two weeks long. It began with 2-1/2 days of plenary sessions which covered the research programs of CERN, Frascati, KEK, Novosibirsk, Orsay and SLAC. The next 5-1/2 days were devoted to 7 working groups. There were many talks given in each working group, and there was a lively exchange of ideas between groups. During the final 2 days there were summaries of the working groups which have been published in Ref. 1. There were 113 participants at the workshop with 28 from outside the U.S.

Table 2. Summaries of Working Groups

Topic	Speakers
Parameters	A. Hutton, P. Wilson
RF Power	J. LeDuff
Structures	I. Wilson, G. Loew
Final Focus	P. Chen, B. Autin
Beam Dynamics	R. Ruth
Damping Rings	A. Mikchailichenko, J. Delahaye T. Raubenheimer, L. Rivkin
Instrumentation	C. Johnson, J. Seeman

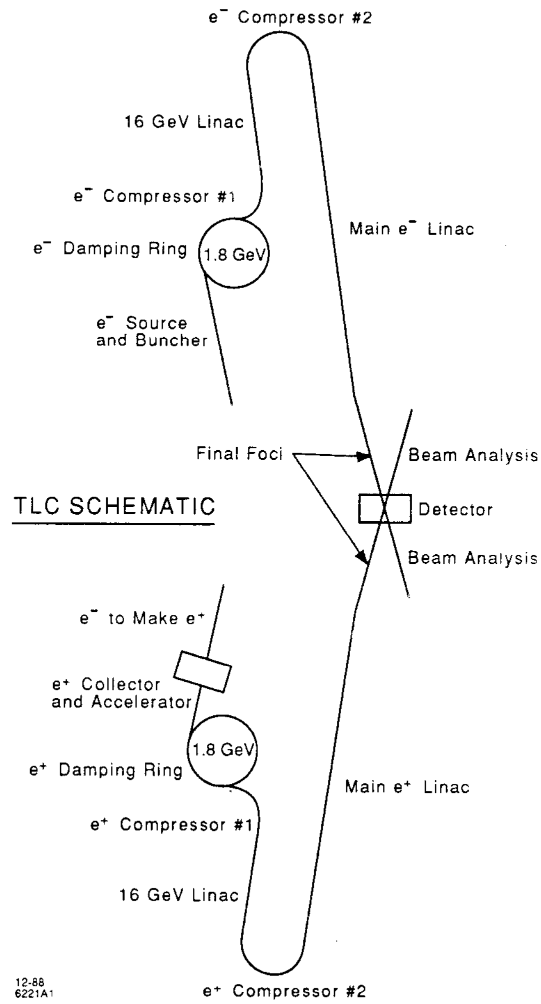

Fig. 1 Schematic layout of the TLC.[2]

In Table 1 you see a list of the working groups together with chairmen and scientific secretaries. The difficult job of the preparation of summary talks was given to those people listed in Table 2. Before beginning a discussion of each working group, it is useful to see an overall layout of an NLC. In Fig. 1 you see a schematic for the TeV Linear Collider (TLC) at SLAC. In order to save space on the site and to keep the injection complex close together, the beams most likely will be born heading away from each other. In the TLC case a dedicated linac is envisaged for positron production; however, the VLEPP design uses the spent high energy beam and wigglers to produce polarized e^+ and e^-. At around 2 GeV the beams encounter a damping ring to damp the emittance to acceptable values. After extraction the beams are compressed in length before they are accelerated in a preaccelerator up to about 16 GeV. At this point in the design shown, they are bent around an arc which serves the dual function of the change in direction and further bunch compression.

* Work supported by the Department of Energy, contract, DE–AC03–76SF00515

Presented at the 1989 Particle Accelerator Conference, Chicago, Illinois, March 20–23, 1989.

In some of the other designs this further bunch compression is not used. After this 2nd bunch compression the electrons enter a high-gradient high-frequency linac to be accelerated up to 0.5 TeV for TLC. Other designs range from .25 TeV to 1 TeV for the final beam energy. Notice that the linacs are not necessarily co-linear. After the linac the beams enter the final focus system where they pass through a chromatic correction system with rather gentle bends. They are finally focused to a small spot for collision with a crossing angle so that the debris from the collision can exit through a larger aperture than the final magnet pole tip radius. They then proceed on to a beam dump for analysis of beam-beam deflections, energy, etc.

In the next several sections a brief summary of each working group will be presented. For a more detailed discussion the interested reader is referred to Ref 1.

2. PARAMETERS

The tasks which the parameters working group adopted were first to collect parameter sets and compare them, and second to point out differences in philosophy or style.

In Table 3 you see a selected list of parameters for each of several projects. CLIC stands for CERN Linear Collider; ILC and TLC stand for Intermediate Linear Collider and TeV Linear Collider (SLAC designs); JLC stands for Japanese Linear Collider; and finally VLEPP is the linear collider being designed at INP in Novosibirsk but which would be built in Sepukhov.

The parameters are listed for comparison purposes and are changing as the designs evolve. The general conclusions of the Parameters Working Group are as follows:

1.) The JLC design is similar to ILC/TLC
2.) The SLAC designs are shorter. This means that TLC has a high acceleration gradient and a high peak-power requirement.
3.) CLIC and VLEPP have larger vertical spot size than the other designs. The lost luminosity is recovered in CLIC by a high repetition rate and in VLEPP by a larger bunch population. CLIC is the only design that is not a flat beam design.
4.) CLIC and VLEPP both envision very long bunch lengths. This yields severe problems with transverse wakefields. The wakefields in these designs are not a small perturbation to the main guide magnet fields.

3. DAMPING RINGS AND SOURCES

There were 10 talks given in the working group on Damping Rings and Sources. The necessary emittances are shown in the parameters shown in Table 3. An example of the TLC Damping Ring is shown in Fig. 2 with the parameters shown in Table 4.

Table 5 shows a comparison of parameters for the damping ring designs for CLIC, TLC and VLEPP. Overall, the designs for CLIC and TLC are rather similar except that the CLIC ring is designed for higher repetition rate and lower current as it should be. The VLEPP design differed in that it is a small ring which uses strong short-period wigglers. Actually it was agreed in all designs that wigglers are desirable, if not essential, to achieve the fast damping times with low emittance. However, no detailed studies of dynamic aperture in wiggler dominated lattices have been done.

In the large rings the damping time is achieved by having many bunches damp simultaneously in the ring. Several other points were discussed:

Table 3. Parameter Comparison

	CLIC	ILC	JLC	TLC	VLEPP
Energy [TeV]	2	0.5	1.0	1.0	2
$\mathcal{L}[10^{33}\ \mathrm{cm^{-2}sec^{-1}}]$	1	1.7	1.7	8	1.0
f_{rep} [Hz]	1700	360	510	360	100
N $[10^{10}]$	0.5	0.7	0.4	1.4	10
Bunches/fill	1	10	15	10	1
Polarization		e^-		e^-	e^+e^-
λ_{RF} [cm]	1.0	1.7	2.6	1.7	2.1
Acc. Grad. [MV/m]	80	93	100	186	100
Fill time [nsec]	12	60		60	70
$\gamma\epsilon_x\ [10^{-6}\mathrm{m}]$	1.6	1.9	3.0	2.7	6
$\gamma\epsilon_y\ [10^{-6}\mathrm{m}]$	0.5	0.02	0.1	0.03	0.06
crossing θ [mrad]	<3	4.2	4.0	4.0	
β_y^* [mm]	0.4	0.09	0.09	0.09	1.0
β_x^* [mm]	30	28	30	27	100
σ_y^* [nm]	12	2.4	3	2.2	10
σ_x^* [nm]	60	420	300	390	1000
σ_z^* [μm]	200	70	80	70	700
Final $(\Delta E/E)_{\mathrm{rms}}$ [%]	0.4	0.2		0.14	1.0

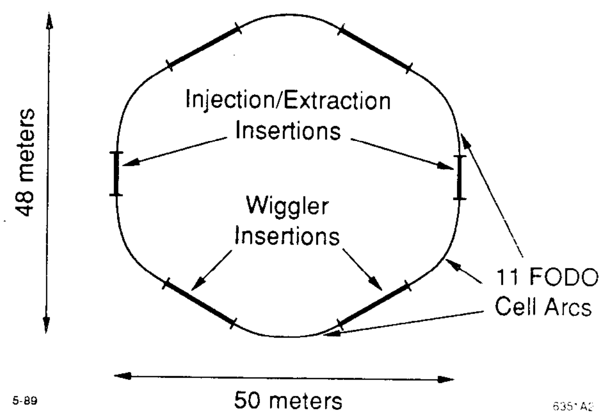

Fig. 2 Schematic of the TLC damping ring.[2]

Table 4. TLC Damping Ring Parameters

Energy	$E_0 = 1.8$ GeV
Length	$L = 155.1$ meters
Momentum Compaction	$\alpha = 0.00120$
Tunes	$\nu_x = 24.37,\ \nu_y = 11.27$
Current	10 batches of 10 bunches of $1.4 \times 10^{10}\ e^+e^-$

1.) Extraction kickers have very tight tolerances on jitter and flatness. Two-kicker designs can improve the situation.

2.) e^+/e^- production is conventional in most designs except for VLEPP where undulator radiation from the spent high energy beam is used to produce polarized $e^\pm$.

3.) All Damping Rings studied must have low impedance. $[(Z/n)_{eff} \simeq 0.2\Omega]$. This is about a factor of 5 better than SLC.

3.) With multiple bunches per RF fill, the rings have many batches of closely spaced bunches. In this case special measures must taken to control multibunch effects (damped RF-cavities).

4.) The possibility of serial rings was discussed in which the rings are either for damping rate or for low emittance.

5.) Overall the outlook was positive . The rings are state of the art but not impossible.

Table 5. Comparison of Damping Ring Designs

	CLIC	TLC	VLEPP
Lattice	Alternated Bends in FODO	FODO	Achromat
Energy [GeV]	2.0	1.8	1.5
Circum. [m]	162	155	77
N $[10^{10}]$	22 of 10×0.5	10 of 10×1.4	20
$\gamma\epsilon_0$ $[10^{-6}\text{mrad}]$	2.1	2.0	3.0
$\gamma\epsilon_{\rm IBS}$ $[10^{-6}\text{mrad}]$ (w/ scattering)	2.1	2.7	6.0
τ_x[msec]	1.1	2.5	1.0
τ_y[msec]	2.7	4.0	1.0
Rad./turn [KV]	793	468	760
RF Voltage [MV]	2.0	0.8	0.9
$f_{\rm RF}$ [GHz]	3.0	1.46	0.5
$\Delta E/E$ [%]	0.17	0.10	0.30
σ_z [mm]	1.4	5.0	8.0
α $[10^{-3}]$	0.2	1.2	0.6
ν_x	22.4	24.37	18.35
ν_y	15.2	11.27	5.69
$L_{\rm wiggler}$ [m]	0	22	12
$B_{\rm peak}$ [KG]	–	24	60

4. BEAM DYNAMICS AND WAKEFIELDS

The task of this working group was to study the preservation of the emittance from the exit of the Damping Ring to the entrance of the Final Focus. There were 13 talks given during the working sessions.

The highlights of the findings are:

1.) Bunches can indeed be compressed to the desired length. For very short bunches (50 μm), 2 stages of bunch compression are necessary; however, the 180° bends that several labs are considering may also serve as compressors.

2.) In the linac transverse wakefields range from weak (JLC, ILC, TLC) to very strong (CLIC, VLEPP). However, all designs contemplate some degree of BNS damping (correlated change in focusing strength along the bunch).

3.) The spread in focusing strength interacts with tolerances for alignment and "jitter" (rapid motion of elements from pulse to pulse). A large spread in betatron wavelength leads to a better jitter tolerance due to loss of memory from filamentation damping. However, this same filamentation leads to tighter alignment tolerances. A small spread in betatron wavelength yields a tighter jitter tolerance but loose alignment tolerances.

4.) For flat beams in the linac the dilution of vertical emittance due to coupling does not seem to be a problem. The direct dilution of the vertical emittance due to chromatic and wakefield effects seems to dominate. Because the beams are so tiny in the linac (2 - 20 μm) all coupling effects are very linear and can be corrected.

5.) To increase luminosity several designs use many bunches per RF fill. To keep the beams stable against beam breakup, it will be necessary to use structures designed to damp higher modes strongly ($Q's \simeq 20$ to 50). This is also a problem in two-beam designs for the drive beam (CLIC). In addition to keeping the beams stable transversely, we must also keep the bunch-to-bunch energy constant to about 0.1%. This yields tight tolerances on RF amplitude and phase and also on the number of particles per bunch.

6.) In order to do physics at the NLC it will be necessary to collimate the beam. However, the wakefield of the collimator can give a kick to the beam that is comparable to the divergence. Engineers would like a big beam (small divergence) whereas beam dynamics dictates a small beam (large divergence) to control the relative wakefield effects. One way out of this dilemna may be to use dynamic collimation with nonlinear fields.

5. RF POWER SOURCES

The power source for an NLC is a fundamental but as yet unsolved problem. This was reflected in a large working group on power sources in which a total of 28 talks were given on various possibilities for power sources. Thus far there are no power source solutions which simultaneously have the peak power, repetition rate, efficiency and cost suitable for an NLC. There are many different sources being considered around the world:

1.) Klystrons. Relativistic Klystrons are being studied at SLAC, LLNL and LBL in a collaborative effort where 180 MW has been achieved in short pulses. ($\simeq$ 30 nsec). Semi-conventional klystrons are being built at SLAC and KEK. These are long pulse devices which would use RF pulse compression described below to achieve high power with short pulse length. High-efficiency multiple-beam klystrons are also being studied at SLAC. Hollow-beam klystrons have been tested at NRL.

2.) Gyrocons have been built at INP in Novosibirsk.

3.) Gyroklystrons are being constructed at the Univ. of Maryland.

4.) The Gigatron is a proposed source being studied at Texas A&M. It uses a flat beam to control space charge effects.

5.) A high-power Crossfield Amplifier is being constructed at SLAC. This device is similar to a magnetron, but is locked to the phase of the input RF.

6.) Lasertrons have been built and are being studied at Orsay, KEK, and Los Alamos.

7.) All the long-pulse power sources discussed above need RF pulse compression to give high power for short pulses. Low-power RF pulse compression has been demonstrated at SLAC, and a high power test is presently under construction.

8.) The Relativistic Klystron discussed above and also the FEL and two beam accelerators discussed below need high-power short pulses to drive them. Magnetic pulse compression plus induction-linac acceleration is being explored at LLNL/LBL for such application.

9.) The first type of two beam accelerator discussed was induction linac driven with either an FEL to extract power or RF structures to extract power. The drive beam is continuously accelerated and decelerated. Both the FEL and RF-structure extraction have been tested experimentally by LLNL/LBL.

10.) Another alternative is to use superconducting RF to accelerate the drive beam and RF structure to extract energy. This being studied at CERN.

Overall there is an ongoing, complimentary, international effort on RF power source development which shows great promise for success.

6. RF STRUCTURES

The programs and plans of all the various laboratories were discussed in some detail in a series of 8 talks presented in the working group on RF structures. Almost everyone is concentrating on disk-loaded travelling-wave structures ($2\pi/3$) with frequencies ranging from 11.4 GHz to 30 GHz. The acceleration gradients being considered ranged from 80 MV/m (CLIC) to 186 MV/m (SLAC).

In order to control transverse wakes, all designs are considering an iris radius $a = 0.2\lambda_{rf}$ which yields $v_g/c \sim 0.1$. Because of the wide range of acceleration gradient and frequency, there is also a wide range in powers necessary, from 130 MW/m to 1.5 GW/m.

For multi-bunch operation it necessary to strongly damp the transverse and higher-order longitudinal modes. Calculations presented in the Beam Dynamics working group indicate that $Q's$ from 20 to 50 may be required. In tests thus far this damping has been achieved with slots in the irises coupled to radial waveguides. Further tests of damped structures will be ongoing.

Other subjects which were discussed included breakdown limits, dark currents, RF processing, fatigue damage, cooling, brazing of structures, alignment, and beam position monitors. Overall, there is much experimental and theoretical work ongoing around the world.

7. INSTRUMENTATION

The instrumentation working group took on a multitude of tasks which were discussed in 13 talks presented during the workshop. The subjects discussed included modeling, beam position monitors (BPMs), beam size monitors, emittance, energy spread, bunch length, alignment, vibration control, control systems, collimation, and monitoring multiple bunches. The measurement of the final spot size was specifically excluded since it is a rather special measurement which depends upon the design of the Final Focus.

There were several main points in the discussion:

1.) Comprehensive instrument packages should be incorporated as part of the design. These should be placed at the optical boundarys between different subsystems and should provide measurements of $\epsilon, \beta, \alpha, \eta, \sigma_E, \sigma_z$, that is, a complete measurement of 6 dimensional phase space. These measurements should be used to confirm matching at the optical boundarys.

2.) The beam position measurements need to have accuracies in the range of 1–10μm depending upon the particular design. Both RF and stripline BPMs were discussed along with associated problems such as dark currents, noise, etc.

4.) The beam size measurement needs to be sensitive in the range 2 - 20μm. This means that wire scanners as used in the SLC Final Focus will work; however, in this case they play the role of the routine beam size measurement.

5.) The energy and energy spectrum must be measured in the bunch compressors and Final Focus since these are the only places with dispersion. It is also possible to have several dedicated beamlines which can destructively monitor energy and energy spectrum.

6.) Traditional methods of alignment are insufficient since alignment tolerances range from 1 - 30μm. As designs evolve it is hoped that these tolerances can be relieved somewhat. However, much work is needed over the next few years to understand how to align an NLC and keep it in alignment. The repetition rate, vibration spectrum, feedback system and site geology all interact to determine beam stability.

7.) To measure the properties of separate bunches in a train with spacings of about 40 cm requires special techniques such as pulsed magnets. It is hoped that only a few of such separate measurements would be necessary.

8.) Bunchlengths can be measured by using the RF to induce a linear correlation of z with E. Then one can use a wire scanner in a dispersive region to measure σ_z. This works well at SLC.

9.) The collimators for an NLC are a fundamental problem. Bunches passing near collimators are deflected by wakefields. Bunches which strike materials may cause single-bunch melting or fatigue due to repetition. Beam halo removal with nonlinear fields may be possible but needs much more study.

8. FINAL FOCUS

The Final Focus working group was another large one which included 26 participants who delivered a total of 23 talks during the workshop. The subjects which were discussed included final-focus optics, beam-beam instrumentation, tolerance to errors, backgrounds, exotic ideas, SLC experience and a Final Focus Test Beam at SLAC.

In Table 6 you see a comparison of parameters for Final Focus systems. The parameters were similar but the detailed optical designs differed greatly. The vertical spot sizes desired are in the range 1 - 20 nm with aspect ratios σ_x/σ_y of 10 - 200. The fundamental limit to the vertical size comes from synchrotron radiation in the final quadrupole combined with the chromatic effect of that quadrupole. This limit (the Oide limit) has thus far not been a problem, but designs tend to be close to the limit.

The crossing angles contemplated prior to the workshop are shown in Table 6. The purpose of this small angle is to provide an exit for the disrupted beam separate from the entrance through the quadrupole. This allows more freedom for the pole-tip radius. As we shall see below this crossing angle proved to be insufficient.

During the workshop there were reviews of beam-beam effects which included disruption, beamstrahlung, disruption angles, kink instabilities, and multi-bunch kink instabilities. All of

Table 6. Comparison of Final Focus Designs

—	CLIC	JLC	TLC	VLEPP	FFTB
Energy [TeV]	1.0	0.5	0.5	1.0	0.05
$\gamma\epsilon_x$ [10^{-6}mrad]	3.0		2.7	6.0	30
$\gamma\epsilon_y$ [10^{-6}mrad]	1.0		0.027	0.06	3–30
β_x^* [mm]	22		30	100	34
β_y^* [mm]	0.4		0.04	1	0.1
σ_x^* [nm]	180	300	260	1000	3000
σ_y^* [nm]	20	3	1	10	55–170
σ_z^* [μm]	200	80	80	500	1000
D_x			0.03	0.1	
D_y	3		6	10	
Υ	0.5		0.3		
Pole field [KG]	14		14		14
Quad radius [mm]	1–2.5		0.5		5
l^* [m] (IP to final quad)	<2.5		0.4		0.4

these effects provide limitations in the design process, but there were no fundamental problems. For example, beamstrahlung can be controlled without loss of luminosity by the use of flat beams. The disrupted beam can be handled with a small crossing angle. The kink instability actually makes the beams less sensitive to offsets since they attract and collide anyway. Multibunch kink instabilities can also be controlled by suitable choices of parameters.

However, there was a new beam-beam effect discovered during the workshop which will have a large impact on the final focus design. This effect is called beamstrahlung pair creation. After a beamstrahlung photon is emitted, it finds itself in the very strong collective field of the opposing bunch. Therefore, the photon can radiate an e^+e^- pair. The corresponding incoherent effect has been known for some time (although its importance was just realized); however, for high energy colliders the coherent effect dominates. For typical parameters the number of e^+e^- pairs produced is in the range $10^6 - 10^8$. This swarm of electrons can produce severe background problems unless dealt with in the interaction point design.

The basic problem is that the diagonal angle of the flat beam does not provide enough crossing angle to create a large exhaust port for the collision. R. Palmer suggests the solution called crab crossing in which the bunches are deflected by an RF deflector as shown in Fig. 3.[2] In this method the bunches are tipped transversely by one-half the crossing angle so that they collide head on, but with a center of mass that is moving horizontally slightly. This allows one to increase the crossing angle without losing luminosity. With such a large angle it is then possible to have large exhaust hole through the final quadrupole without disturbing the pole tip geometry.

In spite of the existance of chromatically corrected designs with large demagnification ($\sim$ 500), there is general agreement that such a design should be tested experimentally to concretely address tolerances, tuning and the measurement of small spots. Not only are the final spots small they are optically demagnified an order of magnitude more than the SLC beam is at the SLC final focus.

Towards this end a Final Focus Test Beam (FFTB) has been

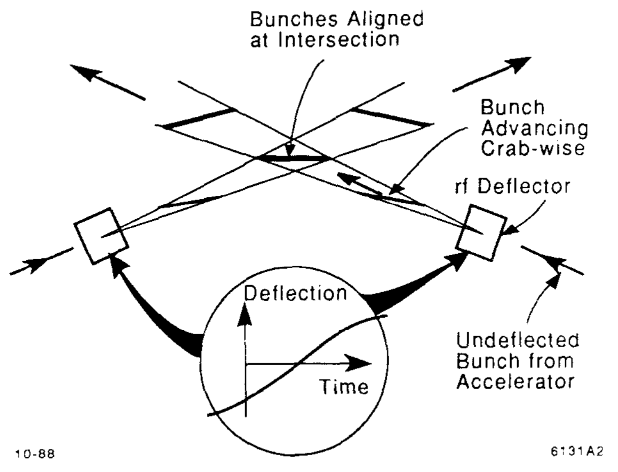

Fig. 3 Schematic of crab crossing in the Final Focus.[2]

proposed which uses the 50 GeV SLC beam straight ahead into the old C-line at SLAC. The purpose of the design is to study the large demagnification optics for Linear Colliders and to also provide a test bed for beam position monitors, beam size monitors, new alignment techniques, final focus quadrupoles and techniques for measuring the final spot. The goal is to provide a beam spot $(\sigma_x, \sigma_y) = (1, .06)\mu$m. The workshop saw the beginnings of an international collaboration to construct the Final Focus Test Beam.

9. OUTLOOK

To conclude this summary of the Linear Collider Workshop let us examine the overall outlook. With regard to parameters, there are many different designs; however, as we learn more they seem to be converging somewhat. The Damping Rings seem to be straightforward although somewhat exotic. Flat beam production seems possible with reasonable tolerances. Beam Dynamics Studies will continue with more work on correction techniques to improve tolerances. There is no RF power source yet but there are many candidates. The next few years may see a power source emerge. Tests with structures are ongoing. Damped RF structures are being designed and tested. Instrumentation for an NLC needs much more work. This must be done early in the design as the impact is large. Much work needs to be done on alignment and stability.

The Final Focus work will move on to more detailed studies of tuning for small spots and the required tolerances. In this regard the Final Focus Test Beam at SLAC will be an essential experimental tool. With the discovery of beamstrahlung pair production there needs to be much more work on interaction point designs with crab crossing to understand and cure the background problems.

Overall, there is much work to be done; however, the path seems to be much clearer now. If the interest at the various laboratories around the world and the participation at this workshop are any indication, then we may be on the road to several "Next Linear Colliders".

REFERENCES

1. Proc. of the Int. Workshop on next Generation Linear Colliders, Nov. 28-Dec. 9, 1988 SLAC, Stanford, CA, SLAC-335.
2. Linear Collider Working Group Reports from Snowmass '88, Ed. R. D. Ruth, SLAC-Report-334 (1989).