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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 25 from outside the U.S.

Table 2. Summaries of Working Groups

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

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Fig. 1. Schematic layout of the TLC.

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.

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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 YLC. Other designs range from 25 TeV to 1 TeV for the final beam energy. Notice that the linacs are not necessarily collinear. 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 TILC 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, TILC.
2. The SLAC designs are shorter. This means that ILC 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 TILC 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, ILC and VLEPP. Overall, the designs for CLIC and ILC 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
$L^{1/4} (10^{13} \text{ cm}^2 \text{ sec}^{-1})$	1	1.7	1.7	8	1.7
$f_{rep} (Hz)$	1700	300	500	300	100
$N \times 10^{10}$	0.5	0.7	0.1	1.4	1.5
Bunches/bil	1	10	15	10	1
Polarization					0.56
$\Delta E (\mu eV)$	1.0	1.7	2.6	1.7	2.5
Acc. Grad. (MV/m)	80	94	100	186	100
Full time (sec)	12	60		60	70
$\sigma_x (10^{-7} \text{ m})$	1.6	1.0	1.6	2.7	6
$\sigma_y (10^{-7} \text{ m})$	0.5	0.92	0.1	0.03	0.9
cross. g. # (rad)	8.3	1.2	1.0	1.0	
$\beta_x^* (\text{mm})$	0.1	0.09	0.09	0.09	1.0
$\beta_y^* (\text{mm})$	30	2	30	27	100
$\sigma_x^* (\text{nm})$	12	24	3	2.2	70
$\sigma_y^* (\text{nm})$	60	120	300	300	1000
$\sigma_z^* (\mu m)$	200	70	80	70	700
Final $\epsilon \Delta E / E (\text{nm}^{-1})$	0.1	0.2		0.1	1.0

Fig. 2. Schematic of the TILC damping ring

Table 4. TILC Damping Ring Parameters

Energy	$E = 1.8 \text{ GeV}$
Length	$L = 155 \text{ meters}$
Maximum Compactness	$\alpha = 0.00120$
Lines	$L_1 = 21.47, L_2 = 11.27$
Current	10 bunches of 100 bunches of 1.1×10^{10} electrons

- 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^+ .
- 3) All Damping Rings studied must have low impedance ($Z/\omega_{rf} \approx 0.2\Omega$). This is about a factor of 5 better than SLC.
- 4) With multiple bunches per RF fill, the rings have many batches of closely spaced bunches. In this case special measures must be taken to control multibunch effects (damped RF cavities).
- 5) The possibility of serial rings was discussed in which the rings are either for damping rate or for low emittance.
- 6) Overall the outlook was positive. The rings are state of the art but not impossible.

Table 5. Comparison of Damping Ring Designs

	CLEIC	TLC	VLEPP
Lattice	Alternated Bends in FODO	FODO	Achromat
Energy [GeV]	2.0	1.8	1.5
Circumf. [m]	162	155	77
N [10 ¹⁰]	22 of 10 x 0.5	10 of 10 x 1.4	20
σ_{ex} [10 ⁻⁶ mrad]	2.1	2.0	3.0
σ_{ex} [10 ⁻⁶ mrad] w. scattering	2.1	2.7	6.0
τ_z [nsec]	1.1	2.5	1.0
τ_y [nsec]	2.7	4.0	1.0
Rad. turn [kV]	793	468	760
RF Voltage [MV]	2.0	0.8	0.9
f_{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
v_z	22.4	24.37	18.35
v_y	15.2	11.27	5.69
$L_{wiggler}$ [m]	0	22	12
B_{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 ($\approx 50 \mu\text{m}$), 2 stages of bunch compression are necessary; however, the 180° bends that several labs are considering may also serve as compressors.

- 2) In the linear transverse wakefield range from $\omega_{rf} \approx 10^4$ to 10^6 Hz, TLC to very strong CLEIC, VLEPP. However, these designs contemplate some degree of BNS damping, a correlated change in focusing strength along the beamline.
- 3) The spread in focusing strength interacts with the spread for alignment and "jitter" (rapid motion of elements from pulse to pulse). A large spread in betatron wavenumber leads to a better jitter tolerance due to loss of energy from filamentation damping. However, this same filamentation leads to tighter alignment tolerances. A large spread in betatron wavelength yields a tighter jitter tolerance but looser 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 ($\approx 20 \mu\text{m}$), all coupling effects are very linear and can be corrected.
- 5) To increase luminosity several designs use multiple 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 ($Q/s \approx 20$ to 50). This is also a problem in two beam designs for the drive beam (CLEIC). In addition to keeping the beams stable transverse, 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 wakewheel 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 wakewheel effects. One way out of this dilemma 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, LBNL and LBL in a collaborative effort where 180 MW has been achieved in short pulses. 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, a proposed source being studied at Texas A&M, it uses a flat beam to control space charge effects.
- 5) A high power threshold Amplifier is being constructed at SLAC. This device is similar to a magnetron, but is locked to the phase of the input RF.
- 6) Lasertons have been built and are being studied at Orsay, KEK and LBNL.

 

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lost breath at 51 yr.

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8. FINAL NOTES

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The co-factors for an $N(\cdot)$ are a function in $\mathcal{H}$, well at SFC.

6. The co-factors passing near co-ordinates are defined as follows:

Fields: Fields which contain marks in a certain state
Branches: Branches which contain marks in a certain state
Composed with $\text{field}(\cdot)$ or $\text{branch}(\cdot)$:
 $\text{field}(\cdot) \rightarrow$ field
 $\text{branch}(\cdot) \rightarrow$ branch
The co-factors for an $N(\cdot)$ are a function in $\mathcal{H}$, well at SFC.

8. Both hypotheses can be tested by using a chi-square test of independence. The null hypothesis is that there is no association between the variables. The alternative hypothesis is that there is an association between the variables. The test statistic is calculated as follows:

Human studies

everyday use. It is hoped that a new generation of teachers will be trained in the use of the computer, and that this will be followed by a new generation of students. However, more work is needed in the area of teacher education. Although the use of computers in education is growing, it is still in its infancy. More research is needed to determine the most effective ways to use computers in the classroom. This research should focus on the development of effective instructional materials, the training of teachers, and the evaluation of the impact of computer-based instruction on student learning. Only through such research can we hope to realize the full potential of computers in education.

1. The first step is to identify the problem or question that needs to be answered. This involves understanding the context and the specific requirements of the task.

1. The first group of people who are not in the majority are the people who are not in the majority.

1. The first step is to identify the problem or goal. This involves understanding the current situation, identifying the problem, and setting a clear goal. For example, if the goal is to increase sales, the first step would be to identify the current sales level and the factors that are affecting it.

1. The first part of the paper is devoted to the study of the
 2. properties of the function $f(x)$ defined by the
 3. equation $f(x) = \int_0^x f(t) dt$. It is shown that
 4. the function $f(x)$ is continuous and differentiable
 5. on the interval $[0, 1]$. The function $f(x)$ is
 6. also shown to be a solution of the differential
 7. equation $f'(x) = f(x)$. The function $f(x)$
 8. is then shown to be the unique solution of this
 9. equation satisfying the initial condition $f(0) = 1$.
 10. The function $f(x)$ is then shown to be the
 11. unique solution of the differential equation
 12. $f'(x) = f(x)$ satisfying the initial condition
 13. $f(0) = 1$. The function $f(x)$ is then shown
  
 84. the initial condition $f(0) = 1$. The function
 85. $f(x)$ is then shown to be the unique solution
 86. of the differential equation $f'(x) = f(x)$
 87. satisfying the initial condition $f(0) = 1$.
 88. The function $f(x)$ is then shown to be the
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 90. $f'(x) = f(x)$ satisfying the initial condition
 91. $f(0) = 1$. The function $f(x)$ is then shown
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 93. equation $f'(x) = f(x)$ satisfying the initial
 94. condition $f(0) = 1$. The function $f(x)$ is
 95. then shown to be the unique solution of the
 96. differential equation $f'(x) = f(x)$ satisfying
 97. the initial condition $f(0) = 1$. The function
 98. $f(x)$ is then shown to be the unique solution
 99. of the differential equation $f'(x) = f(x)$
 100. satisfying the initial condition $f(0) = 1$.

1. The first group of people, who are not yet 18 years old, are not allowed to work.

$$\begin{aligned}
\frac{1}{2} \frac{d}{dt} \int_{\mathbb{R}^n} |u|^2 dx &= \int_{\mathbb{R}^n} u \frac{du}{dt} dx = \int_{\mathbb{R}^n} u \left(-\operatorname{div}(\nabla u) + \nabla u \cdot \nabla u \right) dx \\
&= \int_{\mathbb{R}^n} -u \operatorname{div}(\nabla u) dx + \int_{\mathbb{R}^n} u \nabla u \cdot \nabla u dx \\
&= \int_{\mathbb{R}^n} \operatorname{div}(u \nabla u) dx - \int_{\mathbb{R}^n} |\nabla u|^2 dx + \int_{\mathbb{R}^n} u \nabla u \cdot \nabla u dx \\
&= \int_{\mathbb{R}^n} \operatorname{div}(u \nabla u) dx - \int_{\mathbb{R}^n} |\nabla u|^2 dx + \frac{1}{2} \frac{d}{dt} \int_{\mathbb{R}^n} |u|^2 dx
\end{aligned}$$
$$P_{\text{loss}}(\text{cost}) = \frac{1}{N} \sum_{i=1}^N \left(\frac{1}{2} \left(\frac{1}{\sigma^2} \right) \left(\frac{1}{\sigma^2} \right) \left(\frac{1}{\sigma^2} \right) \right)$$

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The first step in the process is to identify the problem. This is done by gathering information about the problem and its causes. Once the problem is identified, the next step is to develop a plan of action. This plan should outline the steps that need to be taken to solve the problem. Once the plan is developed, the next step is to implement the plan. This involves putting the plan into action and monitoring the progress. Finally, the last step is to evaluate the results. This involves assessing the effectiveness of the plan and making any necessary adjustments.

INSTRUMENTATION

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(3) The subjects which were discussed included breakdown limits, drink amounts, RF processing, fatigue, cooling, and heating of structures, and heat-position monitors. (4) That there is much experimental and theoretical work to do.

[illegible]

but multi-beam operation is necessary to strongly damp the transverse and higher-order longitudinal modes. (Table 1)

$\Delta V_{18} = 1.41 \text{ V}$ and $\Delta V_{19} = 1.41 \text{ V}$

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6 REFERENCES

- [illegible]

Table 6. Comparison of Final Focus Designs

	CLIC	JLC	ILC	VLEPP	LEP
Energy [TeV]	1.0	0.5	0.5	1.0	0.05
σ_{fx} [10 ⁻⁶ mrad]	3.0		2.7	6.0	.30
σ_{fy} [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_{fx}^* [nm]	180	300	260	1000	3000
σ_{fy}^* [nm]	20	3	1	10	75-170
σ_{fx}^* [μ m]	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
β^* [m]	1-2.5		0.4		0.4
IP to final quad					1

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. Most bunch 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 collect velocity 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. 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 existence of chromatically corrected designs with large demagnification ($\sim 500\times$), 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.

proposed which uses the 50 GeV SLC beam straight along 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 $(\sigma_x, \sigma_y) \sim (1, 0.06) \mu\text{m}$. 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. Infrastructure 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 picture 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".

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