Executive Summary

INTRODUCTION

As this report is being published, the international high energy physics (HEP) community finds itself confronting a set of fascinating discoveries and new questions regarding the nature of matter and its fundamental particles and forces. The observation of neutrino oscillations that indicates that neutrinos have mass, measurements of the accelerating expansion of the universe that may be due to dark energy, and evidence for a period of rapid inflation at the beginning of the Big Bang are stimulating the entire field. Looming on the horizon are the potential discoveries of a Higgs particle that may reveal the origin of mass and of a whole family of supersymmetric particles that may be part of the cosmic dark matter. For the HEP community to elucidate these mysteries, new accelerators are indispensable.

At this time, after careful deliberations, all three regional organizations of the HEP community (ACFA in Asia, HEPAP in North America, and ECFA in Europe) have reached the common conclusion that the next accelerator should be an electron-positron linear collider with an initial center-of-mass energy of 500 Giga-electronvolts (GeV), later upgradable to higher energies, and that it should be built and operated in parallel with the Large Hadron Collider under construction at CERN. Hence, this second report of the International Linear Collider Technical Review Committee (ILC-TRC) comes at a very timely moment. The report was requested by the International Committee on Future Accelerators (ICFA) in February 2001 to assess the current technical status of electron-positron linear collider designs in the various regions. Note that the ILC-TRC was not asked to concern itself with either cost studies or the ultimate selection process of a machine.

This Executive Summary gives a short outline of the genesis of the report, the charge given to the committee, and its organization. It then presents a brief description of four electron-positron linear collider designs at hand. The methodology used to assess these designs is described in some detail. The assessments are followed by a list of R&D tasks recommended by the committee for the next few years. The tasks are ranked according to certain specific criteria. The summary concludes with a few remarks outlining upcoming developments that may guide ICFA and the HEP community in their future plans to promote and execute an international project.

The Executive Summary stands alone in the sense that it allows a busy reader, who may not have the time to read the entire report, to become familiar with its essential contents.

GENESIS, CHARGE, AND ORGANIZATION

The ILC-TRC was originally created by the Interlaboratory Collaboration for R&D toward TeV-Scale Electron-Positron Linear Colliders at a meeting in London, England, in June 1994. By the end of 1995, the ILC-TRC produced its first report which for the first time gathered in one document the current status of eight major e^+e^- linear collider designs in the world. As each design progressed, large tables that listed all the major parameters of the machines in the report were updated regularly until the beginning of 2000. By that time, while three of the original eight designs had been abandoned, the five remaining ones had greatly matured.

In 2001, as a result of deliberations at the ICFA meeting of February 8 and 9 at DESY, Professor H. Sugawara as Chair of ICFA requested that the ILC-TRC reconvene its activities to produce a second report. G. Loew, the original Chair of the ILC-TRC, agreed to conduct this second study. ICFA also recommended that a Steering Committee of four members be formed within the ILC-TRC to represent the major e^+e^- linear collider designs in the world to be covered in the second report: TESLA, JLC-C, JLC-X, NLC, and CLIC. Accordingly, R. Brinkmann from DESY was chosen for TESLA, K. Yokoya from KEK for JLC-C and JLC-X, T. Raubenheimer from SLAC for NLC, and G. Guignard from CERN for CLIC. In practice, the designs of JLC-X and NLC became essentially identical, and hence only four basic designs remained to be examined.

The Chair and the full Steering Committee met for the first time at Snowmass, Colorado, on July 5, 2001. During this meeting, the committee reviewed the charge that had been broadly sketched by ICFA and converged on the approximate contents of the report to be produced. The charge was streamlined during subsequent months, and the final version is summarized as follows:

SECOND ILC-TRC CHARGE:

- To assess the present technical status of the four LC designs at hand, and their potential for meeting the advertised parameters at 500 GeV c.m. Use common criteria, definitions, computer codes, *etc.*, for the assessments
- To assess the potential of each design for reaching higher energies above 500 GeV c.m.
- To establish, for each design, the R&D work that remains to be done in the next few years
- To suggest future areas of collaboration

The Steering Committee decided to accomplish its mission by dividing it into two major parts:

- Descriptions of the four machines, their upgrade paths and respective test facilities, setting the foundations for the assessments
- Assessments of the four machines as outlined by the charge

The Steering Committee took full responsibility for the first activity and decided that the assessments should be carried out by two separate Working Groups: one for **Technology, RF Power, and Energy Performance** chaired by D. Boussard, recently retired from CERN, the other for **Luminosity Performance** chaired by G. Dugan from Cornell. The Chair submitted this proposed plan to the ICFA meeting in Rome, Italy, on July 27, 2001, and ICFA accepted the proposal.

From then on, all the work of the ILC-TRC was done via e-mail, teleconferences, and four pivotal meetings. The two Working Groups each consisted of their Chairs and thirteen scientists selected from the Linear Collider world community. During the course of their assessments, the Working Groups realized that a third task, common to both of them, would be of key importance to the ultimate commissioning and successful operation of any of the linear colliders. This task was labelled **Reliability, Availability, and Operability**, and several members of both Working Groups formed a third Working Group to handle this task. All pertinent details can be found in Chapter 1. The overall organization of the second ILC-TRC is summarized in Table 1.

TABLE 1
Second ILC-TRC Overall Organization

Chair	Gregory Loew
Steering Committee	Reinhard Brinkmann Kaoru Yokoya Tor Raubenheimer Gilbert Guignard
Working Groups	
Technology, RF Power, and Energy Performance Assessments	Daniel Boussard
Luminosity Performance Assessments	Gerry Dugan
Reliability, Availability and Operability	Nan Phinney Ralph Pasquinelli

The Table of Contents for this report is fairly self-explanatory. This Executive Summary was written by the Chair, who incorporated numerous comments from the entire committee. Chapter 1, also written by the Chair, summarizes the ILC-TRC's procedures, organization, and milestones. T. Raubenheimer volunteered to be the central "keeper" responsible for putting together the six megatables given in Chapter 2. Chapter 3 on descriptions of the four machines at 500 GeV c.m., Chapter 4 on the upgrade paths to higher energies, and Chapter 5 on the test facilities and other project R&D programs, were written by the members of the Steering Committee for their respective projects. Chapters 6, 7, and 8, presenting the respective assessments of the three Working Groups, were assembled by their Chairs from text prepared by the Subgroup Chairs, with the help of their respective members. Finally, Chapter 9, which summarizes the lists and ranks of all the R&D studies still deemed necessary, was put together by D. Boussard and G. Dugan. It should be noted here that the Working Group members did not always agree with all the statements made by the machine proponents in Chapters 3, 4, and 5, and these disagreements are reflected in their assessments.

BRIEF DESCRIPTIONS OF THE FOUR LINEAR COLLIDER DESIGNS

Even though the final technology choice for an international electron-positron collider has not yet been made, the HEP community agrees that the machine should start with an energy of 500 GeV c.m. and be expandable later to higher energies. While all linear collider designs have undergone remarkable progress in the past 15 years, the machines reviewed here are not all in the same state of readiness. TESLA is most advanced in terms of the rf system feasibility tests mainly conducted at TTF (DESY). JLC-C consists only of a 400 GeV c.m. rf design based on technology being developed for a linac-based FEL at SPring-8 in Japan. JLC-X/NLC have an rf design based on ongoing tests at NLCTA and ASSET (SLAC). Both TESLA and JLC-X/NLC have fairly mature conceptual designs. CLIC follows a more novel approach based on a two-beam system studied at CTF (CERN), but it needs more time to be developed. If successful, CLIC could eventually reach 3 TeV c.m. within a footprint similar to the other schemes. Aside from the rf systems, all of the machines have benefited from advanced tests at FFTB (SLAC) and at ATF (KEK), and from experience with the first linear collider, the SLC, which operated at SLAC from 1988 through 1998. The SLC experience has been essential in understanding the luminosity potential of these four designs.

Note that throughout the report, the committee concentrated its studies on e^+e^- colliders. In most cases, it was assumed that e^-e^- collisions would not require major design changes, although the luminosities would be lower, and that $\gamma\gamma$ collisions would be considered in detail later.

TESLA

TESLA's main characteristics and parameters are shown in Table 2 and illustrated in Figure 1, Figure 2, and Figure 3. The DESY site length is currently fixed at 33 km. The main linacs are based on 1.3 GHz superconducting technology operating at 2 K. The cryoplant, of a size comparable to that of the LHC, consists of seven subsystems strung along the machines every 5 km. RF accelerator structures consist of close to 21,000 9-cell niobium cavities operating at gradients of 23.8 MV/m (unloaded as well as beam loaded)

TABLE 2: Summary of Machine Parameters

	TESLA		JLC-C		JLC-X/NLC[a]		CLIC	
Center of mass energy [GeV]	500	800	500	1000	500	1000	500	3000
RF frequency of main linac [GHz]	1.3		5.7	5.7/11.4[b]	11.4		30	
Design luminosity [10^{33} cm^{-2}s^{-1}]	34.0	58.0	14.1	25.0	25.0 (20.0)	25.0 (30.0)	21.0	80.0
Linac repetition rate [Hz]	5	4	100		150 (120)	100 (120)	200	100
Number of particles/bunch at IP [10^{10}]	2	1.4	0.75		0.75		0.4	
$\gamma\varepsilon_x^*$ / $\gamma\varepsilon_y^*$ emit. at IP [m·rad × 10^{-6}]	10 / 0.03	8 / 0.015	3.6 / 0.04		3.6 / 0.04		2.0 / 0.01	0.68 / 0.01
$\beta_x^\star$ / β_y^* at IP [mm]	15 / 0.40	15 / 0.40	8 / 0.20	13 / 0.11	8 / 0.11	13 / 0.11	10 / 0.05	16 / 0.07
$\sigma_x^\star$ / σ_y^* at IP before pinch[c] [nm]	554 / 5.0	392 / 2.8	243 / 4.0	219 / 2.1	243 / 3.0	219 / 2.1	202 / 1.2	60 / 0.7
$\sigma_z^\star$ at IP [μm]	300		200	110	110		35	
Number of bunches/pulse	2820	4886	192		192		154	
Bunch separation [nsec]	337	176	1.4		1.4		0.67	
Bunch train length [μsec]	950	860	0.267		0.267		0.102	
Beam power/beam [MW]	11.3	17.5	5.8	11.5	8.7 (6.9)	11.5 (13.8)	4.9	14.8
Unloaded/loaded gradient[d] [MV/m]	23.8 / 23.8[e]	35 / 35	41.8/31.5	41.8/31.5 / 70/55	65 / 50		172 / 150	
Total number of klystrons	572	1212	4276	3392/4640	4064	8256	448	
Number of sections	20592	21816	8552	6784/13920	12192	24768	7272	44000
Total two-linac length [km]	30	30	17.1	29.2	13.8	27.6	5.0	28.0
Total beam delivery length [km]	3		3.7		3.7		5.2	
Proposed site length [km]	33		33		32		10.2	33.2
Total site AC power[f] [MW]	140	200	233	300	243 (195)	292 (350)	175	410
Tunnel configuration[g]	Single		Double		Double		Single	

[a]Numbers in ( ) for the JLC-X/NLC correspond to the NLC design with 120 Hz repetition rate.

[b]The 1 TeV JLC-C collider uses a C-band rf system for the first 200 GeV of each linac followed by an X-band rf system for the remaining 300 GeV of acceleration—the X-band rf system would be identical to that described for the JLC-X band collider.

[c]For all designs except CLIC, the IP spot sizes are calculated as usual from the emittances and beta functions. With the design emittances in CLIC, nonlinear aberrations in the final focus system increase the final spot size by 20 to 40%.

[d]The main linac loaded gradient includes the effect of single-bunch (all modes) and multibunch beam loading, assuming that the bunches ride on crest. Beam loading is based on bunch charges in the linacs, which are slightly higher than at the IP.

[e]With the present site layout for TESLA, 23.4 MV/m was the required energy gain per meter of accelerator structure. A detailed analysis by the ILC-TRC revealed that the gradient has to be increased to 23.8 MV/m when rf phasing, especially for BNS damping, is taken into account.

[f]Total site power includes AC for linac rf and cooling systems as well as power for all other beam lines and site facilities.

[g]The single tunnel layout has both the klystrons and accelerator structures in the main linac tunnel while the double tunnel layout places the klystrons and modulators in a separate enclosure. In the CLIC scheme, the main linac uses a single tunnel since there are no klystrons or modulators associated with it. The 300 m-long CLIC drive beam accelerator is located in a tunnel with a separate klystron gallery on the surface.

for 500 GeV c.m. operation. These cavities are supplied with rf power in groups of 36 by 572 10 MW klystrons and modulators. The rf pulse length is 1370 μs and the repetition rate is 5 Hz. At a later stage, the machine energy may be upgraded to 800 GeV c.m. by raising the gradient to 35 MV/m. So far, TTF at DESY has had fairly extensive operation of two cryomodules at 15–18 MV/m for FEL runs, and one module was tested up to 21.4 MV/m with beam, which is close to the design value of 23.8 MV/m. A few 9-cell electropolished cavities have reached 35 MV/m in test cryostats. The upgrade will be achieved by raising the number of klystrons to 1212 and reducing the repetition rate to 4 Hz. The capacity of the original cryoplant will be doubled.

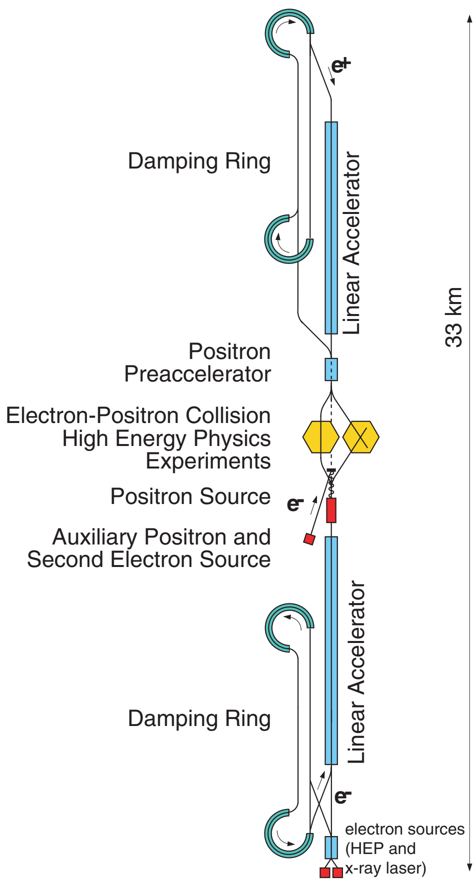

FIGURE 1. TESLA layout

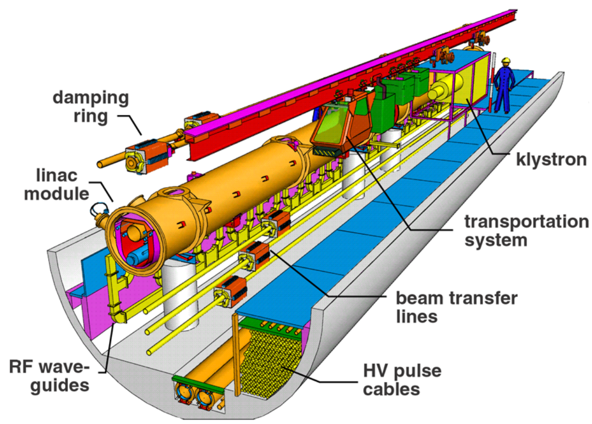

FIGURE 2. Sketch of the 5 m diameter TESLA linac tunnel

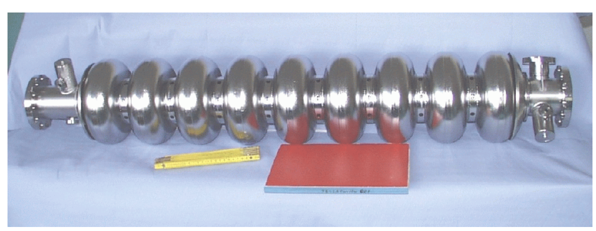

FIGURE 3. The 9-cell niobium cavity for TESLA

All the major TESLA beam parameters are listed in Table 2. Because of the long rf pulses, the bunch trains and bunch spacing can also afford to be long: 950 μs (860 μs) and 337 ns (176 ns) at 500 GeV c.m. (800 GeV c.m.). These parameters have two major consequences: (1) a fast bunch-to-bunch feedback can be used to correct orbits within one beam pulse, and a fast safety system can turn off the beam within a fraction of a pulse; (2) the bunch trains from the electron and positron sources have to be compressed by a factor of about 17 to fit into long 5 GeV damping rings, 17 km in perimeter. These damping rings are "dog-bone" shaped so that their long straight sections can be located in the same tunnels as the linacs, the klystrons, the high-voltage cables, and other beam transfer lines. A 5 GeV electron source is located at one end.

The positron bunch train is produced by a "bootstrap" operation, which uses gamma rays radiated by the primary electron beam passing through an undulator at the end of the linac. The gamma rays impinge on a thin titanium target and the extracted positron bunches are sent to a positron pre-accelerator on the other side of the IR, after which they are stored in the positron damping ring. The proposed design for the primary IR assumes head-on collisions. The design luminosity is 34 (58)$\times 10^{33}$ cm^{-2}s^{-1} for 500 (800) GeV c.m. Even if the 500 GeV c.m. machine is not upgraded but the cavities are built to sustain 35 MV/m from the beginning, the energy can be increased to 700 GeV c.m. at a reduced luminosity of 12$\times 10^{33}$ cm^{-2}s^{-1} by turning down the beam current.

JLC-C

The JLC-C is limited to an rf design using main linacs running at 5.7 GHz up to 400–500 GeV c.m. The idea is that it could be built with layouts, injectors and beam specifications very similar to JLC-X/NLC, described in the next section, and that it might be extended later using X-band technology up to 1 TeV. The rf system is shown in Figure 4 and consists of 1696 units, each with pairs of 50 MW klystrons, pairs of SLED-I type compact rf pulse compressors, and four so-called "choke mode" accelerator structures for higher-order mode suppression. The unloaded gradient is about 42 MV/m and the beam-loaded gradient is about 32 MV/m, resulting in a two-linac length at 5.7 GHz of 17 km for a 400 GeV c.m. energy.

JLC-X/NLC

The JLC-X and NLC are now essentially unified into a single design with common parameters given in Table 2 and shown in Figure 5 and Figure 6. The main linacs are based on 11.4 GHz, room temperature copper technology. The full site is approximately 32 km long. The electron and positron injectors are independent and located at opposite ends. The electron source produces polarized electrons that are accelerated to 2 GeV in an S-band linac, stored in a damping ring, and then again accelerated in a 6 GeV S-band pre-linac. The positrons are generated by an electromagnetic shower from 6 GeV electrons accelerated by an S-band linac, which collide with three parallel tungsten-rhenium targets. These positrons are collected and accelerated to 2 GeV in a large acceptance L-band linac and sequentially damped in a pre-damping and a main damping ring. Then, after two stages of longitudinal compression, electrons and positrons are ready for acceleration in their respective X-band linacs. Three bypass lines are provided along the way to extract particles respectively at 50, 175, and 250 GeV for collisions at two possible interaction points, one for a low-energy detector, the other for a high-energy detector. Crossing angles at the high energy and low energy IRs are 20 and 30 mrad respectively in the NLC design. In the JLC-X, the high energy IR has a crossing angle of 7 mrad.

The main linacs operate at an unloaded gradient of 65 MV/m, beam-loaded to 50 MV/m. These gradients have been achieved in test accelerator structures; structures with the

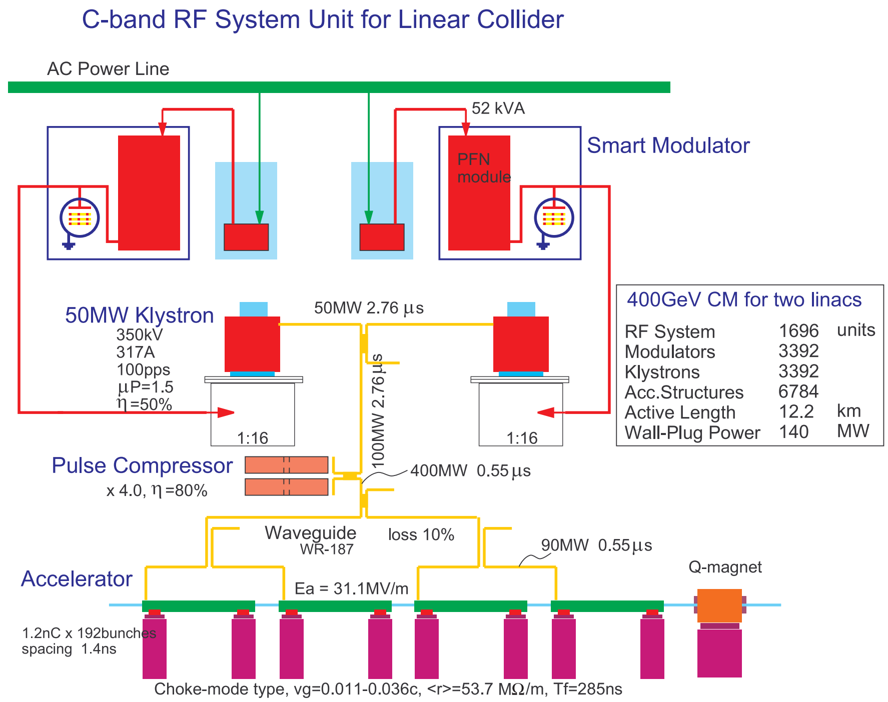

FIGURE 4. Schematic of a JLC-C linac rf unit (one of 848 per linac)

required damping characteristics are under development. The rf systems and accelerator structures are located in two parallel tunnels for each linac. For 500 GeV c.m. energy, these rf systems and accelerator structures are only installed in the first 7 km of each linac. The upgrade to 1 TeV is obtained by filling the rest of each linac, for a total two-linac length of 28 km. The rf systems for 500 GeV c.m. consist of 4064 75 MW Periodic Permanent Magnet (PPM) klystrons arranged in groups of 8, followed by 2032 SLED-II rf pulse compression systems similar to those originally tested at the NLC Test Accelerator at SLAC in 1996. The 12,192 accelerator structures are of a damped-detuned design engineered to suppress deleterious higher-order modes. The structures are mounted on rigid but remotely movable girders. The bunch trains have 192 bunches, with a separation of 1.4 ns at a repetition rate of either 120 or 150 pulses per second. Design luminosity ranges between 20 and 30×10^{33} cm^{-2}s^{-1}, depending on repetition rate and final energy. If one decreases the beam currents by a factor of about 7, then an energy of 1.3 TeV c.m. may be obtained with a gradient of roughly 65 MV/m at a luminosity of about 5×10^{33} cm^{-2}s^{-1}.

CLIC

An overall schematic layout of the CLIC complex is shown in Figure 7. The main linac rf power is produced by decelerating a high-current (150 A) low-energy (2.1 GeV) drive beam (DB), shown in Figure 8. In the short (300 m), low-frequency DB accelerator, a long beam pulse is efficiently accelerated in fully loaded structures. With a delay loop and two combiner rings, this pulse is cut into short segments which are interleaved, simultaneously

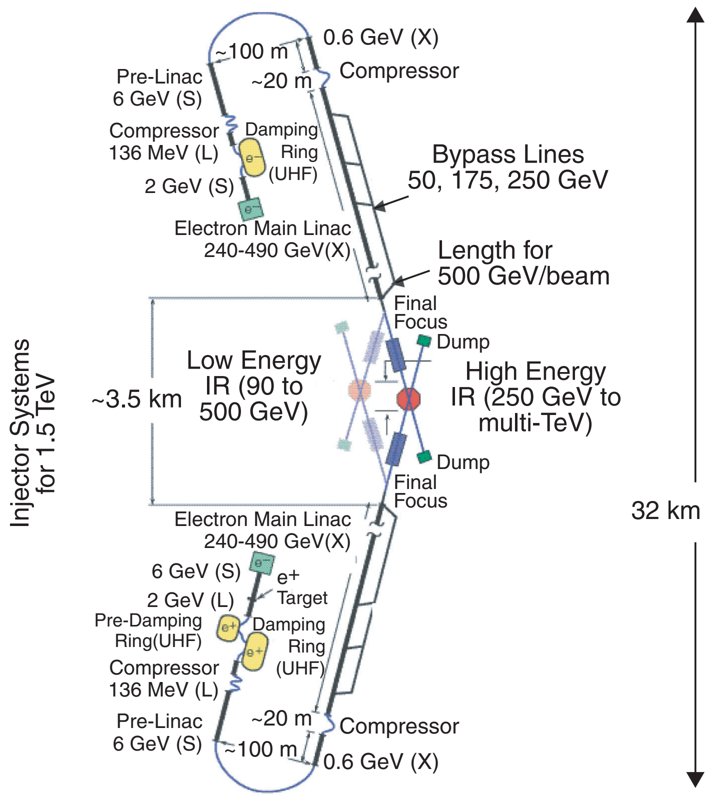

FIGURE 5. JLC-X/NLC layout

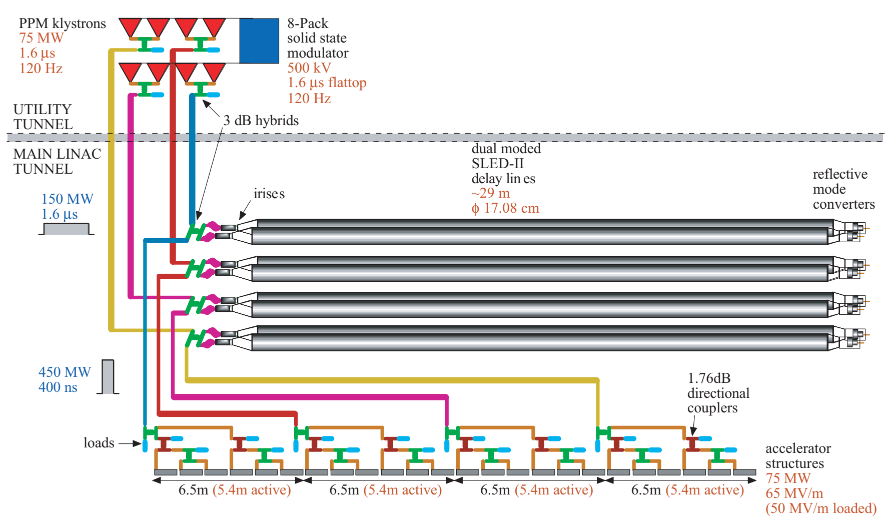

FIGURE 6. Schematic of a JLC-X/NLC linac rf unit (one of 254 per linac)

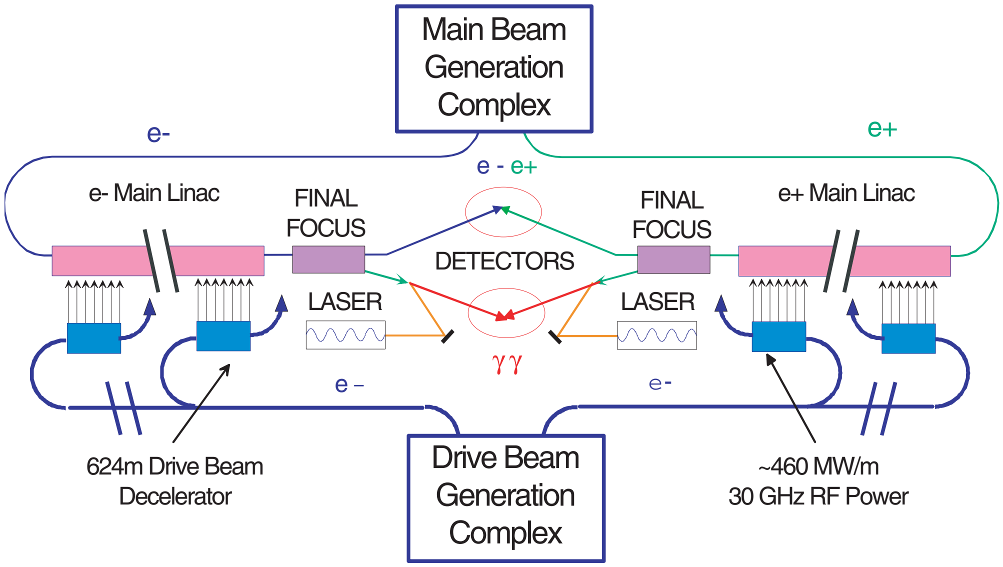

FIGURE 7. CLIC layout (two-linac length at 500 GeV c.m. is 5 km)

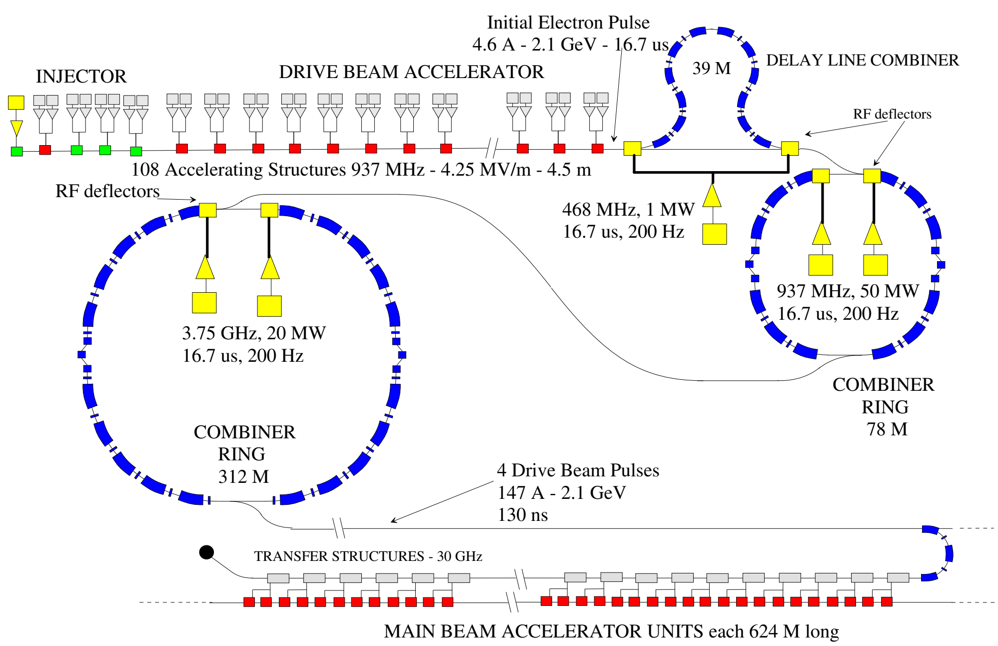

FIGURE 8. Drive-beam generation complex

increasing the pulse frequency and peak current. The resulting four beam pulses of 130 ns each are sent upstream where they are bent around to feed the four DB decelerators, which are parallel to the main linac in a common tunnel. Each of the 450 power-transfer structures of one decelerator produces the rf power feeding two main linac accelerator structures, each with 230 MW. The nominal accelerating gradient of 150 MV/m (corresponding to 172 MV/m unloaded gradient) has been achieved in short test structures without damping and with a pulse shorter by a factor of about 8 compared to the nominal pulse. The two-linac length (~3600 structures per linac) is 5 km.

The main-beam and drive-beam generation is centralized in the middle of the collider. This layout allows the concentration of all the klystrons and modulators, making the maintenance easier and sharing the hardware for electron and positron production. The system is similar to that of JLC-X/NLC; it provides polarized or unpolarized electrons and unpolarized positrons. Different schemes to create polarized positrons are under study.

Upgrades up to 3 TeV c.m. can be obtained by adding more DB decelerators upstream on each side and by increasing the length of the pulse in the DB accelerator to obtain more DB trains after the combiner rings. The total length of the machine is 33 km at 3 TeV c.m. The main-beam injection complex and the DB generation remain the same except for the length of the 937 MHz klystron pulse.

The beam characteristics are found in Table 2. The repetition rate is 200 Hz at 500 GeV c.m. and 100 Hz at 3 TeV c.m. The bunch trains are 100 ns long with a bunch separation of 0.67 ns. Design luminosity goes from 21×10^{33} cm^{-2}s^{-1} at 500 GeV c.m. to 80×10^{33} cm^{-2}s^{-1} at 3 TeV c.m. Two detectors can be accommodated in CLIC. One of them may be used for $\gamma\gamma$ collisions (Figure 7). The beam delivery system is 2×2.6 km long. It is designed for 3 TeV c.m. but has a layout which can be kept unchanged at lower energies.

METHODOLOGY

As mentioned earlier, the assessments of the four linear colliders were carried out by three separate working groups, which in turn subdivided their tasks as follows:

1. Technology, RF Power and Energy Performance:
   - Injectors, Damping Rings and Beam Delivery
   - Power Sources (Klystrons, Power Supplies, Modulators and Low Level RF)
   - Power Distribution (RF Pulse Compression, Waveguides, Two-beam)
   - Accelerator Structures
2. Luminosity Performance
   - Electron and Positron Sources (up to Damping Rings)
   - Damping Rings
   - Low Emittance Transport (from Damping Rings to IP)
   - Machine Detector Interface

3. Reliability, Availability and Operability
    - Compilation of data from existing machines
    - Component reliability issues
    - Machine Protection Systems
    - Commissioning, tuning, and maintenance

The groups assessed their respective systems and topics for all machines, examining schedules and milestones for all the systems, large and small. They summarized their positive reactions as well as their concerns about all relevant design details, then translated their concerns into R&D topics and milestones required to mitigate these concerns. About 120 R&D issues were addressed. The ILC-TRC as a whole then ranked the R&D issues according to the following four criteria:

Ranking 1: R&D needed for feasibility demonstration of the machine

The objective of these R&D items is to show that the key machine parameters are not unrealistic. In particular, a proof of existence of the basic critical constituents of the machines should be available upon completion of the Ranking 1 R&D items.

Ranking 2: R&D needed to finalize design choices and ensure reliability of the machine

These R&D items should validate the design of the machine, in a broad sense. They address the anticipated difficulties in areas such as the architecture of the subsystems, beam physics and instabilities, and tolerances. A very important objective is also to examine the reliability and operability of the machine, given the very large number of components and their complexity.

Ranking 3: R&D needed before starting production of systems and components

These R&D items describe detailed studies needed to specify machine components before construction and to verify their adequacy with respect to beam parameters and operating procedures.

Ranking 4: R&D desirable for technical or cost optimization

In parallel to the main stream of R&D needed to build a linear collider, there should be other studies aimed at exploring alternative solutions or improving our understanding of the problems encountered. The results of the Ranking 4 R&D items are likely to be exploited for improved technical performance, energy upgrades, or cost reduction.

OVERALL ASSESSMENTS

- Upon studying all the machines, the ILC-TRC did not find any insurmountable obstacles to building TESLA, JLC-X/NLC, or JLC-C in the next few years and CLIC in a more distant future. This means that the ILC-TRC could not prove that any of these machines could not be built, given enough time, effort, and resources. The ILC-TRC also noted that the TESLA linac rf technology for 500 GeV c.m. is the most mature. Having said this, the ILC-TRC found through the methodology described above that many R&D topics should still be addressed between now and the time any one of the machines reaches the final construction stage. Of the 120 R&D issues that were identified, about 40 issues were common to all machines (which could generate collaborations between various labs) and the remaining issues were distributed among individual machines.

- The ILC-TRC felt that insufficient funding is currently available to adequately advance the state of all the machines in parallel, a comment that should encourage international collaboration.
- The ILC-TRC also felt that several of the existing Test Facilities are not exploited as effectively as needed to accomplish the necessary R&D, either because of lack of resources or because they are shared with other users.
- Finally, the ILC-TRC felt that linear colliders of the proposed size and complexity require much greater attention to reliability, availability, and operability than has been given before, and that substantial R&D items, in particular those under R1 and R2 listed here, need to be urgently addressed to ensure that the design specifications can be reached and commissioning does not take too long.

RANKING OF RECOMMENDED R&D ISSUES

Specific concerns and assessments (which are described in great detail in Chapter 6, Chapter 7, and Chapter 8) resulted in targeted R&D tasks ranked in categories R1, R2, R3, and R4 listed in Chapter 9. Only R1 and R2 tasks are included here in the Executive Summary, both because of space and because they lead to important conclusions for the immediate future.

Ranking 1

TESLA Upgrade to 800 GeV c.m.

Energy

The Energy Working Group considers that a feasibility demonstration of the machine requires the proof of existence of the basic building blocks of the linacs. In the case of TESLA at 500 GeV, such demonstration requires in particular that s.c. cavities installed in a cryomodule be running at the design gradient of 23.8 MV/m. This has been practically demonstrated at TTF1 with cavities treated by chemical processing[1]. The other critical elements of a linac unit (multibeam klystron, modulator and power distribution) already exist.

- The feasibility demonstration of the TESLA energy upgrade to about 800 GeV requires that a cryomodule be assembled and tested at the design gradient of

[1] Knowing that electropolished cavities sustain significantly higher gradients than chemically polished cavities, there is little doubt that cryomodules running at about 24 MV/m can be built.

35 MV/m. The test should prove that quench rates and breakdowns, including couplers, are commensurate with the operational expectations. It should also show that dark currents at the design gradient are manageable, which means that several cavities should be assembled together in the cryomodule. Tests with electropolished cavities assembled in a cryomodule are foreseen in 2003.

JLC-C

Energy

- The proposed choke-mode structures have not been tested at high power yet. High power testing of structures and pulse compressors at the design parameters are needed for JLC-C. Tests are foreseen at KEK and at the SPring-8 facility in the next years.

JLC-X/NLC

Energy

- For JLC-X/NLC, the validation of the presently achieved performance (gradient and trip rates) of low group velocity structures—but with an acceptable average iris radius, dipole mode detuning and manifolds for damping—constitutes the most critical Ranking 1 R&D issue. Tests of structures with these features are foreseen in 2003.
- The other critical element of the rf system is the dual-moded SLED-II pulse compression system. Tests of its rf power and energy handling capability at JLC-X/NLC design levels are planned in 2003. As far as the 75 MW X-band PPM klystron is concerned, the Working Group considers the JLC-X PPM-2 klystron a proof of existence (although tested only at half the repetition rate). A similar comment can be made regarding the solid-state modulator tested at SLAC.

CLIC

Energy

- The presently tested CLIC structures have only been exposed to very short pulses (30 ns maximum) and were not equipped with wakefield damping. The first Ranking 1 R&D issue is to test the complete CLIC structures at the design gradient and with the design pulse length (130 ns). Tests with design pulse length and with undamped structures are foreseen when CTF3 is available (April 2004).
- The validation of the drive beam generation with a fully loaded linac is foreseen in CTF3. Beam dynamics issues and achieving the overall efficiency look challenging.

Reliability

- In the present CLIC design, an entire drive beam section must be turned off on any fault (in particular on any cavity fault). CLIC needs to develop a mechanism to turn off only a few structures in the event of a fault. At the time of writing this report, there is no specific R&D program aimed at that objective but possible schemes are being studied.

Ranking 2

TESLA

Energy

- To finalize the design choices and evaluate reliability issues it is important to fully test the basic building block of the linac. For TESLA, this means several cryomodules installed in their future machine environment, with all auxiliaries running, like pumps, controls, *etc.* The test should as much as possible simulate realistic machine operating conditions, with the proposed klystron, power distribution system and with beam. The cavities must be equipped with their final HOM couplers, and their relative alignment must be shown to be within requirements. The cryomodules must be run at or above their nominal field for long enough periods to realistically evaluate their quench and breakdown rates. This Ranking 2 R&D requirement also applies to the upgrade. Here, the objectives and time scale are obviously much more difficult.
- The development of a damping ring kicker with very fast rise and fall times is needed.

Luminosity

Damping Rings

- For the TESLA damping ring particle loss simulations, systematic and random multipole errors, and random wiggler errors must be included. Further dynamic aperture optimization of the rings is also needed.
- The energy and luminosity upgrade to 800 GeV will put tighter requirements on damping ring alignment tolerances, and on suppression of electron and ion instabilities in the rings. Further studies of these effects are required.

Machine-Detector Interface

- In the present TESLA design, the beams collide head-on in one of the IRs. The trade-offs between head-on and crossing-angle collisions must be reviewed, especially the implications of the present extraction-line design. Pending the outcome of this review, the possibility of eventually adopting a crossing-angle layout should be retained.

Reliability

- The TESLA single tunnel configuration appears to pose a significant reliability and operability risk because of the possible frequency of required linac accesses and the impact of these accesses on other systems, particularly the damping rings. TESLA needs a detailed analysis of the impact on operability resulting from a single tunnel.

JLC-C

Energy

- The klystrons and modulators should be tested successfully at the nominal 100 Hz repetition rate.
- This should lead to the full test of the linac subunit, with beam. This will include klystrons, modulator, pulse compression system, LLRF control and several structures in their future environment.

JLC-X/NLC

Energy

- There must be a full test of the JLC-X PPM klystron at the specified repetition rate of 120 or 150 Hz.
- These klystrons should be tested with the NLC modulator (at full specs and including arcing tests) and form part of a linac subunit test. The latter should also comprise the dual-moded SLED-II complete system, several damped and detuned structures, installed in the accelerator environment (with temperature control, for instance), and LLRF and controls systems. The test should be made with beam. The present plan is to perform this sort of test with a full girder of structures (some of them being detuned and damped) in 2004.

CLIC

Energy

- Present tests have demonstrated the advantages of tungsten and molybdenum irises in reaching the highest gradients in accelerator structures. These tests should be pursued, possibly also with other materials, for application to CLIC and possibly other machines.
- The very high power of the drive beam and its stability are serious concerns for CLIC. The drive beam stability should be validated, and the drive beam Machine Protection System, which is likely to be a complex system, should be designed to protect the decelerator structures.
- The test of a relevant linac subunit with beam is required. This is one of the purposes of CTF3, which should start operation in 2004.

- The validation of the proposed multibeam klystron performance is needed to finalize the design choices for the CLIC drive beam generation. This applies particularly to the 3 TeV energy upgrade (long pulse).

Luminosity

Low Emittance Transport

- Calculations of the effects of coherent synchrotron radiation on the CLIC bunch compressors must be performed.

Machine-Detector Interface

- An extraction line design for 3 TeV c.m. must be developed.

Items Common to All Machines

Luminosity

Damping Rings

- For all the damping ring designs, further simulation studies are needed to understand the magnitude of the electron cloud effects and to explore possible means of suppressing these effects. Experiments in existing rings are needed to test the electron cloud simulations. Possible cures for the electron cloud (including chamber coatings, superimposed magnetic fields, and gaps in the bunch pattern) need to be experimentally investigated.
- Further simulations of the fast ion instability are also necessary. Experiments in the ATF and other suitable rings are needed to test the predictions of these simulations.
- Damping ring extraction kicker stability, required at the level of $<10^{-3}$, is an important issue. Continued studies including experiments with the ATF double kicker system are needed.
- Finally, additional simulations of emittance correction in the damping rings are needed, including the effects listed in Section 7.2.3.2. Additional experiments in the ATF and other operating rings are needed to test the emittance correction algorithms.

Low Emittance Transport

- For all low emittance transport designs, the static tuning studies, including dynamic effects during correction, must be completed.
- The most critical beam instrumentation, including the intra-train luminosity monitor, must be developed, and an acceptable laser-wire profile monitor must be provided where needed in each design. A vigorous R&D program is mandatory for beam instrumentation in general; it would be appropriate for a collaborative effort between laboratories.
- A sufficiently detailed prototype of the main linac module (girder or cryomodule with quadrupole) must be developed to provide information about on-girder sources of vibration.

Reliability

- A detailed evaluation of critical subsystem reliability is needed to demonstrate that adequate redundancy is provided and that the assumed failure rate of individual components has been achieved.
- The performance of beam based tuning procedures to align magnets and structures must be demonstrated by complete simulations, in the presence of a wide variety of errors, both in the beam and in the components.

OVERALL IMPACT OF RELIABILITY ON PEAK AND INTEGRATED LUMINOSITY

As one looks at high energy particle colliders around the world, it is becoming increasingly clear that designing them for high peak luminosity is only part of the game. Designing for high integrated luminosity is just as essential. Both are crucial to keep up with the decrease of physical cross-sections with increasing c.m. energy.

The ILC-TRC spent considerable time and effort discussing the problem of reliability, availability, and operability, and the results of these discussions are summarized in Chapter 8. Much work has been done but much more is needed, regardless of which machine is selected. Unlike for storage rings, every pulse for a linear collider is a complete cycle from beginning to end. Experience with the SLC at SLAC from 1988 to 1998 showed that such a machine cannot reach its peak luminosity unless the hardware is reliable and machine tuning algorithms are highly automated. Without these conditions, the process of improving the luminosity does not converge. Furthermore, the major obstacles in running the SLC efficiently turned out to arise not from the linac rf system (which can be tested with prototypes), but from the damping rings, the positron source, the arcs, and the final focus. The future LC will not contain arcs but it will have long beam delivery systems with many collimators. None of these systems will be testable ahead of time in their entirety. Extrapolations to a linear collider that will be ten times as long and complex make these considerations even more stringent.

Even so, experience with existing accelerators (outlined in Section 8.3), can guide us by focusing on certain factors which are helpful in realistically estimating integrated luminosity. Four quantities, ST, HA, BE, and NL, are defined here.

ST is the total scheduled calendar time for the machine in a year.

HA is the fraction of time the machine hardware is available to produce beam. Hardware downtime includes both unscheduled repairs (when something critical breaks), scheduled repairs (either at regular intervals or when enough problems have accumulated), and all associated cooldown, warmup, and recovery times. For an accelerator, one must consider not only how long it takes to repair a failed component, but also the total time the beam is off because of the fault, including time lost due to access and the time taken to retune the beam.

BE is the effective fraction of beam time actually delivering luminosity. Beam inefficiencies include Machine Development (time spent studying and improving the accelerator), the impact of tuning procedures, injection, and the luminosity decay during a store (for storage rings), Machine Protection trips and recovery (for linacs), and last but not least, the simple fact that accelerators do not manage to deliver the same luminosity on every pulse or for every store.

NL is the nominal luminosity during a particular run. It may be greater or less than the design luminosity, but it usually increases steadily as the accelerator becomes better understood. For a storage ring, it is the typical luminosity at the beginning of a store. For a linear collider, it is the luminosity when the beams are colliding well.

Multiplying these four quantities together yields the integrated luminosity. The reader may perform such a calculation by making his or her own guesses based on other machines such as those tabulated in Chapter 8 of the report. If, for example, one takes an ST of 6500 hours, an HA of 80% (perhaps somewhat optimistic), a BE of 80% (which includes 10% for Machine Development and 10% for all other inefficiencies), and a hypothetical NL of, say 10×10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, then one gets an integrated luminosity of 150 inverse femtobarns for that year.

The reader is cautioned not to take the above numbers as predictions, but rather to see this example as a reminder to the designers and builders of a linear collider of the importance of reliability, operability, and tunability. If the machine is to deliver its desired performance, the design must be robust, the hardware must be very reliable, the commissioning must proceed rapidly, and the luminosity must approach its design value as rapidly as possible.

ADDED VALUE OF THE ILC-TRC

The ILC-TRC in this report described all the machine designs, assessed them, and ranked the R&D tasks remaining to be done. In addition, the work of the ILC-TRC accomplished the following:

- By its studies, the ILC-TRC directly or indirectly caused significant changes in the various designs. Examples for TESLA and JLC-X/NLC can be found in Chapter 1.
- Perhaps the greatest collaborative contribution of the ILC-TRC was the advancement of beam dynamics simulations for the damping rings and especially for the so-called low emittance transport from the damping rings to the IP. The latter started with perfect machines, introduced static errors likely to exist upon installation, made corrections using Beam Based Alignment (BBA), then introduced dynamic errors from hypothetical ground motions and mechanical vibrations, and finally attempted to estimate luminosity in the presence of these effects. This effort is still a “work in progress” and a future task will be to verify that tuning algorithms still converge in the presence of all dynamic errors.
- Finally, as already seen, the ILC-TRC as a group came up with a significant number of R&D tasks which are common to all machines. These tasks will inevitably foment further collaborations as needs develop, and people and resources become available. How and which of these new collaborations will be formed beyond those which

already exist is a dynamic process that the ILC-TRC did not have time to prescribe. It is likely that these collaborations will develop naturally as needs arise in the coming years.

CONCLUDING REMARKS

Two years have gone by since ICFA requested this second ILC-TRC study. Producing the report has been an exciting and demanding task. The document is obviously not perfect, it is longer than originally planned, there are probably errors, and some of the conclusions may remain controversial and/or incomplete. Much technical work remains to be done, and the international HEP community also needs some time to set the stage for the next steps. These include the selection of a single technology for an international machine and the creation of world institutions that will be able to promote and execute such a large project.

As was mentioned in the Introduction, the charge to the ILC-TRC was to assess the current technical status of the machine designs at hand. It did not include the examination of costs nor the difficult step of technology selection. In spite of this, during the course of the study, many outsiders frequently asked the Chair how he thought the committee's work would help ICFA and the HEP community in the selection process. On this, the Chair cannot speak for the whole committee but he can make a few observations on the developments and choices that lie ahead:

- The timeline to accomplish the R1 tasks listed in this summary depends on a number of factors and varies from machine to machine. As mentioned earlier, TESLA and JLC-X/NLC at present have fairly mature conceptual designs and their main linac rf systems are undergoing intensive tests. The progress of JLC-C will depend on the developments at SPring-8 in Japan and that of CLIC on the developments at the test facilities at CERN.
  - TESLA has essentially demonstrated its main linac rf performance specifications for 500 GeV c.m. By the end of 2003, one will hopefully know if TESLA can reach 800 GeV c.m. by testing of the cryomodules at 35 MV/m.
  - By the end of 2003, one will also hopefully know if JLC-X/NLC can meet its main linac rf systems specifications (equally applicable to 500 GeV and 1 TeV c.m.).
  - JLC-C will conduct a partial test in 2003, comprising a modulator, klystron, and rf pulse compressor feeding one accelerator structure with gradients above the design value. A full rf unit is likely to be tested in 2004 or 2005.
  - By 2007, the results of the CLIC tests in CTF3 will become available, hopefully confirming the concept of drive beam generation and the nominal gradient in accelerator structures with the nominal rf pulse length.
- Assuming the above demonstrations of the TESLA and JLC-X/NLC subsystems are successful within the above schedule, by the beginning of 2004 the two machines will be on an equal footing from the point of view of their rf systems for the main linacs. If at that time the HEP community wanted to make a choice between these two

> technologies, it could do so by weighing all the technical differences between the two machines and the challenges presented by the remaining R2 tasks. Besides their main linacs, this comparison should also include their injectors, positron sources, damping rings, beam delivery systems and interaction regions, as well as their energy reach, luminosity reach, reliability, and probably cost.

Whatever the international HEP community decides to do, the Chair wants to point out that the ILC-TRC brought together a sizeable group of the best linear collider experts in the world. The process taught them how to work as a team, let them be critical of each other's work in a constructive way, and helped them improve each other's designs by pooling their expertise. It is fair to say that there is no group in the world today that has a comparable global grasp of the respective strengths and weaknesses of the four machine designs. As the procedure to select a machine is put into place, the HEP community would be wise to continue to take advantage of this collective expertise. In particular, a mechanism should be found to vigorously pursue the beam dynamics simulations which the ILC-TRC started so successfully but was not able to complete within the time available. And independently of how the future unfolds, the ILC-TRC should have no doubt that through its hard and incisive work, it substantially advanced the cause of the linear collider and hopefully opened the door to its eventual realization somewhere in the world.

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