# REPORT FROM THE INTERNATIONAL LINEAR COLLIDER TECHNICAL REVIEW COMMITTEE

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*Abstract*

The International Linear Collider Technical Review Committee (ILC-TRC), formed in 1994, was reconvened in February 2001 by the International Committee for Future Accelerators (ICFA) to assess the current technical status of all electron-positron linear collider designs at hand in the world: TESLA, JLC-C, JLC-X/NLC and CLIC. The ILC-TRC worked for exactly two years and submitted its report to ICFA in February 2003.

This paper presents the motivation behind the study, the charge to the committee and its organization, a table of machine parameters for 500 GeV c.m. energy and later upgrades to higher energies, the methodology used to assess the designs, and a ranked list of R&D tasks still deemed necessary between now and the time any one of the projects is selected by the HEP community and begins construction. Possible future developments are briefly discussed.

## MOTIVATION, CHARGE AND ORGANIZATION

The international high energy physics (HEP) community at the present time 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.

During the past year, 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) came 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. The study and production of the report took exactly two years. The report was submitted and accepted by ICFA at its February 14, 2003 meeting in Tsukuba, Japan.

The four $e^+e^-$ colliders under consideration were TESLA (1.3 GHz), JLC(C) (5.7 GHz), JLC(X)/NLC (11.4 GHz), and CLIC (30 GHz).

The charge for the second ILC-TRC study is given below:

**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 organization of the ILC-TRC showing the Steering Committee and the Working Groups is given below in Table 1.

Table 1

| | |
|---|---|
| **Chair** | Gregory Loew (SLAC) |
| **Steering Committee** | Reinhard Brinkmann (DESY) |
| | Kaoru Yokoya (KEK) |
| | Tor Raubenheimer (SLAC) |
| | Gilbert Guignard (CERN) |
| **Working Groups** | |
| Technology, RF Power and Energy Performance Assessments | Daniel Boussard (CERN, Retired), Chair |
| Luminosity Performance Assessments | Gerry Dugan (Cornell), Chair |
| Reliability, Availability and Operability | Nan Phinney (SLAC)<br>Ralph Pasquinelli (FNAL), Co-chairs |

The members of the Steering Committee each contributed a complete description of their respective designs and upgrades (see full report [1] and Table 2 for a summary of the principal machine parameters). 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.

## METHODOLOGY USED BY THE WORKING GROUPS

The assessments of the four linear colliders were carried out by the three Working Groups in Table 1, which in turn subdivided their tasks as follows:

### *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

### *Luminosity Performance*

Electron and Positron Sources (up to Damping Rings)
Damping Rings
Low Emittance Transport (from Damping Rings to IP)
Machine Detector Interface

### *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 the machines. They then summarized their positive reactions as well as their concerns about all relevant design details, and 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.

## GENERAL CONCLUSIONS

- The Steering Committee and the three Working Groups reached the following general conclusions:
- LC designs and technologies have made remarkable progress in the last 15 years
- Beam dynamics computer simulations have also made remarkable progress
- The Committee did not find insurmountable showstoppers to build TESLA, JLC-X/NLC or JLC-C in the next few years, and CLIC in a more distant future, given enough resources
- However, significant R&D, which is described below, remains to be done for all designs
- Reliability, availability and operability need much greater attention than given so far (see section on peak and integrated luminosity below).

## RANKING OF RECOMMENDED R&D ISSUES

Specific concerns and assessments are described in great detail in the report [1]. All the R1 tasks and some of the R2 tasks (common to all machines) are reproduced here. The reader who is interested in more details should refer to the full report.

### *Ranking 1 Items*

### *TESLA Upgrade to 800 GeV c.m.*

- The committee considered 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 c.m., 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. 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 c.m. requires that a cryomodule be assembled and tested at the design gradient of 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 were foreseen in 2003.

### *JLC-C*

- 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*

- 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 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*

- 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 the 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.
- 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 Items Common To All Machines*

### *Damping Rings*

- Simulations and experiments to study electron cloud and fast ion instabilities
- Extraction kicker stability $<10^{-3}$ level
- Emittance correction algorithms

### *Low Emittance Transport*

- Static and dynamic tuning studies using beam-based alignment techniques
- Development of critical beam instrumentation, including luminosity monitors
- Main linac module and quadrupole vibration studies

### *Overall Reliability Studies*

- A detailed evaluation of critical subsystems 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

The ILC-TRC spent considerable time and effort discussing the problem of reliability, availability, and operability, and their impact on peak and integrated luminosity which are equally important when one designs a collider. 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 and difficult.

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

- *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 with time. 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. 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 $10x10^{33}cm^{-2}s^{-1}$, 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.

## A POSSIBLE ROADMAP FOR THE FUTURE

During the past year, the respective HEP communities in Asia, Europe and North America have constituted regional steering committees to organize the process that could eventually lead to the construction of an international linear collider. To coordinate their work, an International Linear Collider Steering Committee (ILCSC) has also been formed. A possible roadmap to achieve these goals is briefly outlined below.

- By 2004, the R1 tasks for TESLA and JLC-X/NLC will hopefully be accomplished.
- The ILCSC has already set up international accelerator and detector sub-committees to continue relevant studies. A "wise-persons" committee yet to be formed will recommend the selection of a single accelerator technology on the basis of physics reach, technical and cost comparisons, as the R1 tasks are completed.
- An International LC Design and Management Group will then be created to prepare a unified Technical Design Report and cost estimate in 2-3 years.
- Meanwhile, the three regional steering committees are engaging their respective government agencies to form the necessary international oversight, management and financial institutions to launch the LC.
- Once design and cost estimate are completed, an international decision to proceed can be made: host region(s) will come forward, and an ultimate site will be selected.
- Construction could then begin.

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## REFERENCES

[1] The report may be found on the Web at: http://www.slac.stanford.edu/pubs/slacreports/slac-r-606.html
Copies of the entire report may be obtained by requesting SLAC-R-606 from the following address:
Stanford Linear Accelerator
2575 Sand Hill Road, MS-68
Menlo Park, CA 94025
E-mail address: epubs-l@slac.stanford.edu

Table 2: Summary of Machine Parameters

| | TESLA | | JLC-C | | JLC-X/NLC[*] | | 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[†] | 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 |
| $\beta^*_x$ / $\beta^*_y$ 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 |
| $\sigma^*_x$ / $\sigma^*_y$ at IP before pinch[‡] [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 |
| $\sigma^*_z$ at IP [$\mu$m] | 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 [$\mu$sec] | 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[§] [MV/m] | 23.8 / 23.8[**] | 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[††] [MW] | 140 | 200 | 233 | 300 | 243 (195) | 292 (350) | 175 | 410 |
| Tunnel configuration[‡‡] | Single | | Double | | Double | | Single | |

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

[†] 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.

[‡] 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%.

[§] 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.

[**] 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.

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

[‡‡] 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.