

Final

**International Technology
Recommendation Panel**

Report

**Submitted to the International Linear Collider Steering
Committee (ILCSC) and the International Committee on
Future Accelerators (ICFA)**

September 2004

Executive Summary

Introduction

Particle physics stands at the threshold of discovery. The standard model gives a precise and quantitative description of the interactions of quarks and leptons. Its predictions have been confirmed by hundreds of experimental measurements. Nevertheless, experiments at accelerators and observations of the cosmos point to phenomena that cannot be explained by the standard model. Dark matter, dark energy and neutrino masses all require new physics beyond present understanding. Exploring this new frontier will be the task of twenty-first century particle physics.

The essential first step is to find the Higgs boson, or whatever mechanism takes its place. The Higgs is a revolutionary new form of matter whose interactions give mass to the elementary particles. If it exists, the Higgs should be discovered at the CERN LHC, but measuring its properties with precision will require a TeV-scale electron-positron linear collider. Beyond the Higgs, strong arguments suggest that the TeV scale will be fertile ground for discovery. The LHC will open this new territory, but a TeV-scale linear collider will be necessary to explore it in detail. Higher precision leads to greater understanding and discovery. For these reasons, the global particle physics community has endorsed such a linear collider as the next major step in the field. The case for its construction is firm.

During the past decade, dedicated and successful work by several research groups has demonstrated that a linear collider can be built and reliably operated. There are two competing designs. One, developed by the TESLA collaboration, accelerates beams in 1.3 GHz (L-band) superconducting cavities. The other, a result of joint research by the NLC and GLC collaborations, accelerates beams using 11.4 GHz (X-band) room temperature copper structures. Both R&D programs have verified the proofs of principle for the accelerating structures and the systems that drive them. The critical R&D steps were reviewed in the Technical Review Committee (TRC) charged by the International Committee for Future Accelerators (ICFA) to assess the technical readiness of these designs. The essential R&D milestones identified by the TRC in its 2003 report have now been met.

In 2004, ICFA formed the International Technology Recommendation Panel (ITRP) to evaluate the two technologies and to recommend a single choice on which to base the linear collider. Our Panel met six times from January to August 2004 to hear presentations by the proponents of the two projects, gather input from the wider community, evaluate the information and prepare our recommendation. We requested responses from the proponents to an extensive set of questions. We based our decision on a set of criteria that addressed scientific, technical, cost, schedule, operability issues for each technology, as well as their wider impacts on the field and beyond.

Recommendation and Rationale

The ITRP charge specified a set of design goals for the linear collider. We found that both technologies can achieve the goals presented in the charge. Both have been pursued by dedicated and talented collaborations of physicists and engineers from around the world. Each collaboration has made important contributions that will prove essential to the successful realization of the linear collider.

The details of our assessment are presented in the body of this report. On the basis of that assessment, we recommend that the linear collider be based on superconducting rf technology. This recommendation is made with the understanding that we are recommending a technology, not a design. We expect the final design to be developed by a team drawn from the combined warm and cold linear collider communities, taking full advantage of the experience and expertise of both.

Our evaluation process focused on the major acceleration and beam transfer elements of each design. We also examined other critical components, including the damping rings and the positron source. Both technologies had considerable strengths.

The warm technology allows a greater energy reach for a fixed length, and the damping rings and positron source are simpler. The Panel acknowledged that these are strong arguments in favor of the warm technology. One member (Sugawara) felt that they were decisive.

The superconducting technology has features, some of which follow from the low rf frequency, that the Panel considered attractive and that will facilitate the future design:

- The large cavity aperture and long bunch interval simplify operations, reduce the sensitivity to ground motion, permit inter-bunch feedback, and may enable increased beam current.
- The main linac and rf systems, the single largest technical cost elements, are of comparatively lower risk.
- The construction of the superconducting XFEL free electron laser will provide prototypes and test many aspects of the linac.
- The industrialization of most major components of the linac is underway.
- The use of superconducting cavities significantly reduces power consumption.

Both technologies have wider impact beyond particle physics. The superconducting rf technology has applications in other fields of accelerator-based research, while the X-band rf technology has applications in medicine and other areas.

Next Steps

The choice of the technology should enable the project to move forward rapidly. This will require the engagement of both cold and warm proponents, augmented by new teams from laboratories and universities in all regions. The experience gained from the Stanford Linear Collider and Final Focus Test Beam at SLAC, the Accelerator Test Facility at KEK, and the TESLA Test Facility at DESY will be crucial in the design, construction and operation of the machine. The range of systems from sources to beam delivery is so extensive that an optimized design can only emerge by pooling the expertise of all participants.

The machine will be designed to begin operation at 500 GeV, with a capability for an upgrade to about 1 TeV, as the physics requires. This capability is an essential feature of the design. Therefore we urge that part of the global R&D and design effort be focused on increasing the ultimate collider energy to the maximum extent feasible.

We endorse the effort now underway to establish an international model for the design, engineering, industrialization and construction of the linear collider. Formulating that model in consultation with governments is an immediate priority. Strong central management will be critical from the beginning.

A TeV-scale electron-positron linear collider is an essential part of a grand adventure that will provide new insights into the structure of space, time, matter and energy. We believe that the technology for achieving this goal is now in hand, and that the prospects for its success are extraordinarily bright.

International Technology Recommendation Panel Report

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1. Introduction

Particle physics is entering an extraordinary new era. New discoveries – dark matter, dark energy and neutrino masses – require new physics beyond present understanding. During the next few years, the era will open with the CERN Large Hadron Collider (LHC), a proton-proton collider scheduled to begin operation in 2007. The LHC will discover the Higgs boson, or whatever takes its place. It will explore physics beyond the Higgs and search for other new phenomena, such as supersymmetry, extra spatial dimensions, and physics not yet imagined.

The LHC will be the first to explore the TeV scale, but it alone will not be able to answer all the important questions. For this reason, the global particle physics community is proposing to build an electron-positron linear collider (LC), to operate at energies up to about 1 TeV. With its precise and well-characterized initial state, the linear collider brings complementary discovery capability and the ability to carry out precision measurements necessary to untangle the new physics. For example, the LC can measure the spin and parity of the Higgs boson; it can determine the masses and quantum numbers of the supersymmetric particles; it can measure the number of extra dimensions. The complete science case is set forth in *Understanding Matter, Energy, Space and Time: the Case for the Linear Collider*.¹ A synergistic approach, building on the strengths of each machine, offers the best opportunity for progress.

For more than a decade, collaborations based in Asia, Europe and the United States have made tremendous progress in linear collider R&D. As a result of their work, there is no doubt that a TeV-scale linear collider can be built and successfully operated. Two approaches meet the science requirements and are sufficiently well developed to allow a prompt start: the “warm” or X-band design, pioneered at SLAC and KEK, and the “cold” or superconducting L-band design, proposed by the TESLA collaboration centered at DESY.

The international community believes that it is time to unite behind a single technology and carry out a detailed design and development program. This will permit the LC to be constructed on a timescale that allows overlap with LHC operation. In early 2004, the International Committee for Future Accelerators (ICFA), through its International Linear Collider Steering Committee (ILCSC), formed the International Technology Recommendation Panel (ITRP) to choose between the two technologies. The composition of the Panel, which has members from Asia, Europe and North America, is listed in Appendix A.

At the first ITRP meeting, ICFA chair Jonathan Dorfan said: “Never before has a field of science attempted to globalize itself as extensively as HEP is doing recently. It is a challenging task, but one that we must do successfully. Indeed the long-term health of the field depends critically on truly global cooperation. ICFA is playing a key leadership role in this new global approach. The linear collider is the most visible and most

¹ <http://blueox.uoregon.edu/~lc/wwstudy/>

challenging element of this more global approach – to be successful requires a new paradigm. Key to that paradigm is our need to come together with a common set of technical decisions as the basis of a LC design that truly has the collective ownership of the partners.”

He went on to say, “The next major step towards a global design is the creation of an internationally federated design team. The International Linear Collider Steering Committee (ILCSC) is in the process of establishing such a team. A critical prerequisite for starting the work of the global design team is the requirement of a single option for the rf technology to power the main linacs. Thus ICFA has formed the International Technology Recommendation Panel (ITRP).”

Maury Tigner, chair of the ILCSC, presented the ITRP with its charge, given in Appendix B. He added the statement, “This procedure has an important implication: The recommendation should be based upon inherent characteristics of the underlying technology of the ‘designs’ being studied and not upon the particular engineering choices displayed in that design which have no inherent connection with the basic technology. We should assume that, whatever the recommendation, the very best engineering will be applied to it in the final technical, engineering design.”

This report presents the result of the ITRP study. As described in the report, the consensus recommendation is that the global design effort be based on the cold rf technology.

2. Process

The ITRP carried out its evaluation at six meetings. The meeting agendas are contained in Appendix C.

The first meeting was held in January 2004 at the Rutherford Appleton Laboratory. At this meeting, the ITRP was presented with its charge. In addition, the Panel was briefed on the work of the International Linear Collider Technical Review Committee (ILC-TRC). Experts from the TRC presented the TRC's second report, including detailed analyses of each technology.

The ITRP then visited each of the proponent sites. It heard presentations about the technologies, toured the R&D facilities, and met the relevant communities. These visits occurred in meetings 2 (L-band, at DESY in April), 3 (X-band, at SLAC in April) and 4 (X-band, at KEK in May). The warm C-band option was also presented in meeting 4.

A fifth meeting was held at Caltech in June. The CLIC R&D program was described in that meeting. Issues relating to experimental detectors were also discussed. TRC experts were available for consultation at all five meetings.

As part of its evaluation process, the ITRP developed a set of criteria that it used to evaluate each technology. The criteria were organized into six major areas:

1. The scope and parameters specified by the ILCSC
2. Technical issues
3. Cost issues
4. Schedule issues
5. Physics operation issues
6. General considerations that reflect the impact of the LC on science, technology and society.

The ITRP studied each area to differentiate between the two technologies and to highlight areas that required particular focus. To help with the evaluation, the Panel posed a series of questions to the proponents (Appendix D). The responses² were evaluated in executive sessions during meetings 4 and 5.

The sixth and final meeting was held in August in Pohang, Korea. This meeting was devoted to a more global discussion of the issues and to reaching a final decision. The primary criterion for the technology choice was the ability of the linear collider to meet the required scientific goals.

² http://www.ligo.caltech.edu/~donna/ITRP_Home.htm

3. Evaluation

The ITRP evaluation criteria were organized into six major areas.

3.1 Scope and Parameters

The ILCSC developed the basic parameters that a linear collider must achieve. They are set out in the *Parameters for the Linear Collider* document that may be found on the ICFA web site.³

The Parameters Document describes a baseline machine that allows physics operation at any energy between 200 and 500 GeV. The luminosity of this machine must be sufficient to acquire 500 fb⁻¹ of luminosity in four years of running, after an initial year of commissioning. The baseline machine must be such that its energy can be upgraded to approximately 1 TeV, as required by physics. The upgraded machine should have luminosity sufficient to acquire 1 ab⁻¹ in an additional three or four years of running.

At any energy, the machine should be capable of producing electrons with at least 80% polarization. It must also satisfy stringent stability and calibration requirements necessary for precision physics measurements. Furthermore, it is desirable for the machine to be capable of certain extensions beyond the baseline, including increased luminosity, positron polarization, operation at the Z pole, and operation in e⁻e⁻, e⁻γ, or γγ modes.

The ITRP evaluated each technology in the light of these requirements. It examined technical, cost, schedule and operational issues. The details of the assessment are presented in succeeding sections of this report.

The Panel's general conclusion was that each technology would be capable, in time, of achieving the goals set forth in the Parameters Document. The Panel felt that the energy goals could be met by either technology. The higher accelerating gradient of the warm technology would allow for a shorter main linac. The luminosity goals were deemed to be aggressive, with technical and schedule risk in each case. On balance, the Panel judged the cold technology to be better able to provide stable beam conditions, and therefore more likely to achieve the necessary luminosity in a timely manner.

3.2 Technical Issues

A linear collider consists of two main linacs and a number of other subsystems that are critical for meeting the performance goals. The Panel evaluated the main linacs and subsystems for both technologies to identify performance-limiting factors that might hinder fast construction and commissioning. The factors were characterized in terms of risk and then rated for the whole complex.

³ http://www.fnal.gov/directorate/icfa/LC_parameters.pdf

In general, the Panel found the LC R&D to be far advanced. Over the years, the global R&D effort uncovered a variety of issues that were mitigated through a series of updated designs. For the warm technology, major subsystems were built to study actual performance. The KEK damping ring was constructed to demonstrate the generation and damping of a high-intensity bunch train at the required emittance, together with its extraction with sufficient stability. The Final Focus Test Beam at SLAC was constructed to demonstrate demagnification of a beam accelerated in the linac. As a result, the subsystem designs are more advanced for the warm technology.

The Panel was impressed with the state of CLIC R&D. We felt that CLIC will face many challenges in demonstrating the feasibility of high-current beam-derived rf generation. Nevertheless, it was impressive to see such a vigorous collaboration attacking these issues at CTF3 at CERN. The Panel was also gratified to see the progress on the C-band design. The C-band technology was originally conceived as an alternative to X-band for acceleration up to 500 GeV. We were pleased to see that the technology is feasible and that it can be readily transferred to industry, with applications in science (XFELs) and industry (e.g. medical accelerators).

Over the years, important experience in operating LC systems has been gained at NLCTA at SLAC, GLCTA at KEK, TTF at DESY, and ASSET at SLAC. These facilities made important contributions to the development of diagnostics, controls, feedback systems and to the understanding of long-range wakefield effects. This work, whether directed towards X-band or L-band, will provide valuable lessons for reliable operation, irrespective of the final technology. The experience gained from the SLC, the only linear collider ever operated, will be of utmost importance. The knowledge and experience of the global accelerator community will be essential for creating a successful LC design.

We found that, generally speaking, the cold technology carries higher risk in the accelerator subsystems other than the linacs, while the warm technology has higher risk in the main linacs and their individual components. To understand this in detail, we paid special attention to the modulators, klystrons, pulse compression system, power couplers, cryomodules and copper structures. The results achieved to date indicate that both approaches are feasible, but both still involve significant extrapolation from presently available technology.

The accelerating structures have risks that were deemed to be comparable in the two technologies. The warm X-band structures require demonstration of their ability to run safely at high gradients for long periods of time. The cold superconducting cryomodules need to show that they can manage field emission at high gradients.

For the cold, industrialization of the main linac components and rf systems is now well advanced. The TTF has been at the center of the superconducting rf technology, and should continue to be available until a more distributed infrastructure comes into place. Furthermore, many cold technology components will be tested over the coming few years in a reasonably large-scale prototype through construction of the superconducting XFEL at DESY.

A superconducting linac has a high intrinsic efficiency for beam acceleration, which leads to lower power consumption.

The lower accelerating gradient in the superconducting cavities implies that the length of the main linac in a cold machine is greater than it would be in a warm machine of the same energy. Since the physics program gives a strong motivation for achieving the maximum possible energy, future R&D must stress ways to extend the energy reach to 1 TeV, and even somewhat beyond.

In a superconducting rf structure, the rf pulse length, the length of the bunch train, and interbunch time interval are all large. This offers many advantages, as detailed below. The disadvantages are mainly related to the complex and very long damping rings, and the large heat load on the production target for a conventional positron source, which might require a novel source design.

Storage rings are among the best-understood accelerator subsystems today, and much of this knowledge can be transferred to the linear collider damping rings. Beam dynamics issues such as instabilities, ion effects, and intrabeam scattering have been well studied in those machines. The damping rings for the cold technology require innovative developments, including the reduction of space charge effects by x-y coupling, fast extraction kickers, and stray magnetic field compensation. These problems require careful attention from the combined warm and cold communities. Electron cloud effects in the positron damping ring need special attention for both the cold and warm designs.

The ability to achieve design luminosity in the shortest possible time will be a critical measure of the collider's success. A number of arguments indicate that this will be easier with the cold technology. The cold technology permits greater tolerance to beam misalignments and other wakefield-related effects. It has a natural advantage in emittance preservation because the wakefields are orders of magnitude smaller than in a warm machine. The long bunch spacing eliminates multi-bunch effects and eases the application of feedback systems. This feedback will facilitate the alignment of the nanometer beams at the collision point. It will also simplify the beam protection system since only a fraction of the bunch train is in the linac at any given moment, and the long inter-bunch time allows bunch-by-bunch adjustments. For these reasons, we deem the cold machine to be more robust, even considering the inaccessibility of accelerating components within the cryogenic system.

Detailed consideration of the ground motion requirements also points towards the cold technology. While seismic measurements show the feasibility of warm linear collider operation in many locations, the ultimate site decision will depend on issues out of the designers' control. Under these circumstances a more forgiving technology will allow a larger variety of possible sites. This must be weighed against the fact that lower gradient cold linacs require longer tunnels.

Once the linear collider is operating at design luminosity, it is likely that even higher luminosity will be desired. With the presently designed overhead in the rf systems and the lower sensitivity to wakefields, the cold technology is better suited for intensity upgrades and smaller-emittance beam transport.

No beam has ever been realized with the small emittances, short bunch length, and large number of bunches required in a linear collider. Therefore risks such as electron cloud or ion instabilities cannot be excluded until the machine comes into operation. The long bunch spacing in the cold technology decreases the accumulation of such effects over subsequent bunches and lowers the overall risk.

Our recommendation is for the cold rf technology, but not a specific design. Many issues remain to be addressed by the global design group. Achieving the highest possible gradient is the primary way to guarantee that the LC can react promptly to physics results from the LHC. Towards that end, several high-gradient cryomodules need to be assembled and tested for acceptable field emission. Work to assess the possibility of modifying the cavity shape to permit higher gradients would be welcome.

In developing a new linear collider design based on superconducting rf technology, the global design group needs to devote significant attention to the damping rings. A robust design is necessary because the cold technology requires long damping rings that will be difficult to test prior to construction. The positron production scheme must also be investigated since an undulator-based system can only be fully tested after the LC is built. Other areas needing study include the question of one vs. two tunnels, the design of the rf power couplers to the cavities, and the mechanism for aligning the cold components. Much more attention is needed on beam instrumentation systems, the beam delivery system, as well as beam dynamics and simulations. In all these areas, the combined experience of the warm and cold collaborations will be essential to develop the best possible design.

3.3 Cost Issues

A difference in cost between the two technologies is potentially an important discriminating factor in making the technology recommendation. For that reason, the Panel spent considerable effort gathering and analyzing all information that is available regarding the total costs and the relative costs of the two options. We had presentations by those who performed the various cost estimates and comparisons. These discussions included the DESY costing of the cold TESLA design (based largely on estimates from industry); the SLAC NLC costing of the warm technology (based on experience with the technical components and model extrapolations for construction costs), and KEK GLC warm technology estimates (based mainly on Japanese industry estimates). Finally, we investigated the comparative cost estimates of the two technologies done in the U.S. Linear Collider Technology Options Study, as well as a comparative study done at KEK.

At the present conceptual and pre-industrialized stage of the linear collider project, it must be recognized that uncertainties in estimating the total costs are necessarily large. Although it might be thought that relative costing could be done with more certainty, there are additional complications in determining even the relative costs of the warm and cold technologies because of differences in design choices and differences in costing methods used in different regions. Some of the important contributors to the uncertainties are:

- The design and implementation plans for important technological components of each machine are in a preliminary state.
- Differences in design philosophy by the proponents lead to differences in construction cost, as well as final performance. These cannot be resolved until a global and integrated design exists.
- Assumptions about industrialization/learning curves for some key components have large uncertainties at this early stage in the design.
- Present cost estimates have some regional philosophies or prejudices regarding how the project will be industrialized. Contingency accounting, management overheads, staff costs for construction and R&D costs for components are all treated differently; this adds uncertainty to cost comparisons.
- In an international project, the procurement of substantial parts of the collider will be from outside the regions that prepared the present estimates, and this can considerably alter the costs.
- The costs of operating the accelerator are also difficult to determine at this stage without a better definition of the reliability, access and staffing requirements, as well as the cost of power and component replacement.

As a result of these considerations, the Panel concluded that comparable warm and cold machines, in terms of energy and luminosity, have total construction and lifetime operations costs that are within the present margin of errors of each other.

An independent international cost evaluation would be necessary to reach a more accurate cost evaluation, and even that is premature at this time and should follow a conceptual global design. Therefore we concluded that the cost differences between the two technologies cannot be considered to be an important factor in making the technology recommendation.

3.4 Schedule Issues

The ITRP analyzed schedule issues to assess the effect of each technology on industrializing, constructing and commissioning the linear collider. We studied the proponents' estimates of technically limited schedules for preparing a full Technical Design Report and for subsequent LC construction. We also considered the comparative study of schedule and availability issues presented in the U.S. Linear Collider Technology Options Study.

In accordance with our charge, we assumed that LC construction would start before 2010, and that it would be preceded by a coordinated, globally collaborative effort of research, development, and engineering design. Based on our assessment of the technical readiness of both designs, we concluded that the technology choice will not significantly affect the likelihood of meeting the construction start milestone. We believe that the issues that will drive the schedule are primarily of a non-technical nature.

We note, however, that there are potentially significant schedule-related risks in the areas of industrialization, installation of major subsystems sharing the same housing, commissioning activities, and in achieving the integrated luminosity goal. The construction of the superconducting XFEL free electron laser will provide prototypes and test many aspects of the linac, which gives the superconducting technology some advantage.

After the technology decision, we recommend that the global design effort carry out an independent review of schedule issues, in parallel with more accurate costing. A thorough risk and availability analysis will be an essential ingredient of the final design process and must be integrated into the project from the start.

3.5 Physics Operation Issues

The ultimate goal of the linear collider is to enable experimenters to do physics. Many factors affect day-to-day physics operation, including the efficiency for delivering collisions, the energy spread of the colliding beams, the frequency of breakdowns and the ability to quickly recover from them.

In general, the ITRP concluded that both technologies offered excellent opportunities for cutting-edge physics. However, it was felt that several factors favor the cold machine:

- The long separation between bunches in a cold machine allows full integration of detector signals after each bunch crossing. In a warm machine, the pileup of energy from multiple bunch crossings is a potential problem, particularly in forward directions.
- The energy spread is somewhat smaller for the cold machine, which leads to better precision for measuring particle masses.
- If desired, in a cold machine the beams can be collided head-on in one of the interaction regions. Zero crossing angle might simplify shielding from background. However, a nonzero crossing angle permits the measurement of beam properties before and after the collision, giving added constraints on the determination of energy and polarization at the crossing point.

Furthermore, the Panel believes it important that the final design allows maximum flexibility for physics, including the possibilities of increased luminosity, positron polarization, as well as operation at the Z pole, WW threshold, and in e^-e^- , $e^- \gamma$, or $\gamma\gamma$ modes.

3.6 General Considerations

The ITRP technology decision is an important milestone for the linear collider. It is necessary if the collider is to begin operation in the middle of the next decade. At that time, the only other energy-frontier accelerator will be the CERN LHC. The ITRP

decision should allow the linear collider to move forward quickly, so the two machines can have some period of concurrent operation.

Our evaluation confirms that linear collider R&D is sufficiently advanced for the project to move to design, engineering, industrialization, and construction. The technology is in hand. We endorse the effort now underway to establish an international model for the project. Formulating this model in consultation with governments is an immediate priority. Strong central management will be critical from the beginning.

Installation of two detectors should be foreseen from the start. The two interaction regions could then have different features, allowing increased physics coverage. For example, different detectors could be used to study e^+e^- and $\gamma\gamma$ collisions, or one could be used to measure the precise properties of Z bosons. Two detectors would also increase the overall efficiency of physics operation, since one detector can run while the other is being maintained. Finally, two detectors would provide an important cross check, allowing new scientific results to be confirmed by independent teams.

The cold LC will be the largest superconducting rf facility ever built. The production of about 20,000 high-gradient 9-cell cavities in industry will require very demanding techniques for electropolishing and ultra-clean preparation. This will be an important stimulus for industry. The rf power couplers and the multi-beam high-power klystrons can also be expected to have broader applications.

Linear collider R&D affects other scientific areas as well. For example, the development of high-gradient superconducting cavities is a breakthrough that will find applications in light sources and X-ray free electron lasers, as well as in accelerators for intense neutrino sources, nuclear physics, and materials science. New light sources and XFELs will open new opportunities in biology and material sciences. The superconducting XFEL to be constructed at DESY is a direct spin-off from linear collider R&D. Likewise, the R&D work done for the X-band rf technology is of great interest for accelerators used as radiation sources in medical applications, as well as for radar sources used in aircraft, ships and satellites, and other applications.

For decades, high-energy physics has driven the development of accelerator science. Now, over 10,000 accelerators worldwide are used for medical diagnostics and treatment, advanced materials characterization, the sterilization of food, communications and military applications, as well as for fundamental research in materials science, condensed matter physics, nuclear and heavy ion research, structural biology and environmental studies. It is a priority to keep accelerator science strong in all regions of the world.

The linear collider will be built through global collaboration, building on the CERN model of international collaboration which has been so successful for Europe. The linear collider will provide free access to scientists from all over the world, allowing them to carry out their research at a global facility in international collaboration. We hope that a worldwide collaboration on a project of this magnitude, with all regions retaining ownership and contributing major critical systems, could serve as a model for future international projects in other fields.

4. Findings and Recommendations

The ITRP recommends that the linear collider be based on superconducting rf technology. This recommendation is made with the understanding that we are recommending a technology, not a design. We expect the final design to be developed by a team drawn from the combined warm and cold linear collider communities, taking full advantage of the experience and expertise of each.

The technology recommendation is based on the scope and parameters set forth in the ILCSC Parameters Document. These parameters were motivated by the best present understanding of the physics potential of the linear collider, as guided by the precision data from experiments at CERN, Fermilab and SLAC.

A 500 GeV linear collider, with a luminosity above $10^{34} \text{ cm}^{-2}\text{s}^{-1}$, should easily be capable of detecting the Higgs boson, studying its properties, and determining whether it is responsible for generating the masses of the quarks, leptons, and gauge bosons of the Standard Model. Beyond that, physics might well require a collider energy of 1 TeV or somewhat above. As a consequence, we urge that the final design have a clear and minimally disruptive upgrade path to at least 1 TeV.

We considered many criteria in making our technology recommendation, but first and foremost was the requirement that the machine meet or exceed the physics goals given above. Making the technology choice at this time will allow future efforts to be directed towards producing a technically mature and cost effective final design.

The complementarity between the scientific capabilities of the LHC and the LC argues for a LC schedule that will allow some overlap in operation of the two machines. Our expectation is that following the technology decision, a global effort will establish a final design in about five years. Early results from the LHC will be ready on about the same time scale; we expect that they will help validate the scientific importance of the linear collider.

Over the past twenty years, there has been remarkable technical progress towards the linear collider. The international R&D programs have demonstrated solutions to all major issues. The challenges were formidable and included creating high-gradient accelerating systems at a reasonable cost, controlling nanometer-scale beams, aligning components to extremely high accuracy, and developing intense electron and positron sources with extremely small beam emittances. Although further engineering development is needed, it is clear that a TeV-scale linear collider meeting the science goals can be built and successfully operated in a timely manner.

Because of its size, complexity and cost, the linear collider must be a global project. This was recognized very early and consequently there has been a strong level of international cooperation and communication during the previous R&D phase. Three laboratories, together with many collaborating institutions, have developed alternative designs for a

linear collider. SLAC and KEK developed the NLC/GLC (Next/Global Linear Collider), based on warm X-band rf technology; the TESLA Collaboration centered at DESY proposed TESLA (TeV-Energy Superconducting Linear Accelerator), based on cold L-band rf. Experience gained at the SLAC Linear Collider, the first linear collider ever built, and at dedicated R&D facilities at several laboratories, formed the basis for both sets of designs.

Beginning from extensive technical evaluations already performed on these specific designs, particularly by the Technical Review Committee appointed by ICFA, we evaluated the two competing technologies on a broad range of criteria. The extensive research and successful demonstrations performed for both warm and cold designs led us to confirm that either technology would be a viable choice for the final design of a linear collider. This embarrassment of riches made our decision particularly difficult because we quickly concluded there were no showstoppers or overriding issues that would favor one technology over the other and therefore determine our choice.

We developed an extensive and systematic process for evaluating many criteria for both technologies. These criteria fell into six major areas that are described in the body of this report. Each criterion was analyzed and evaluated in terms of the relative advantages or disadvantages for warm and cold technologies. We examined the extensive existing materials and assessed the answers to specific questions that we posed to the experts and proponents. Our evaluations led to substantial consistency, item by item over the Panel. Our final evaluation and choice was primarily based on integrating over all these evaluations from the twelve Panel members. Although the choice was very close, with some criteria yielding advantages for one technology and others for the other technology, we found a broad and consistent advantage for the cold technology. On that basis, we recommended that the LC design be based on the superconducting rf technology.

We now expect the world community to unite quickly behind the superconducting rf technology as the basis for the main linac in a new globally coordinated design for the linear collider. We expect the work to be carried out by an international consortium of laboratories and universities from Asia, Europe and North America. We firmly believe that this new design effort must begin with as few preconceived ideas as possible and that this approach will lead to the best possible final design.

Finally, we endorse the central Global Design Initiative being proposed by ILCSC and ICFA that will lead and coordinate the efforts of the consortium partners. Most of the actual work will be carried out regionally with resources being provided to the central laboratories in those regions, but it is our firm conviction that a strong central management should be in place as early as possible.

The technology recommendation presented here is just one step in a coordinated effort by the worldwide particle physics community to develop a unified plan for the next large particle accelerator, the International Linear Collider. We look forward to the necessary next steps in making this unique research tool available, enabling a new and deeper understanding of the character of space, time, matter and energy.

Appendix A

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Appendix B

Charge for the International Technology Recommendation Panel

19 November 2003

General Considerations

The International Technology Recommendation Panel (the Panel) should recommend a Linear Collider (LC) technology to the International Linear Collider Steering Committee (ILCSC).

On the assumption that a linear collider construction commences before 2010 and given the assessment by the ITRC that both TESLA and JLC-X/NLC have rather mature conceptual designs, the choice should be between these two designs. If necessary, a solution incorporating C-band technology should be evaluated.

The recommendation should be based on all relevant scientific, technical, schedule and cost considerations. Major references for the Panel will be the recently issued “International Linear Collider Technical Review Committee Second Report 2003” (<http://www.slac.stanford.edu/xorg/ilc-trc/2002/2002/report/03rep.htm>) and the document outlining the case for the electron-positron linear collider “Understanding Matter, Energy, Space and Time” (http://sbhep1.physics.sunysb.edu/~grannis/lc_consensus.html)

To reach its recommendation the Panel will hear presentations from the design proponents addressing the above issues.

The agendas of the presentations will be approved by the Panel in advance to assure uniformity of coverage of the technologies put forward. The Panel may ask for expert advice on any of the considerations listed above, drawing first on the ILCSC and its expert subcommittees, then moving beyond the ILCSC as necessary and appropriate. Relevant input from the world particle physics community will be solicited.

Scientific Criteria

The technology recommended shall be capable of meeting the scope and parameters set forth by the ILCSC, in the document “Parameters for the Linear Collider”, as accepted by the ILCSC on 19 November 2003.

Technical Criteria

Using the ICFA Technical Review Committee report and materials supplied by technical experts that may be called, the Panel will make its recommendation based on its judgment of the potential capabilities of each conceptual design for achieving the energies and the peak and integrated luminosities needed to carry out the currently understood scientific program, as envisioned in the ILC Parameters Document.

Schedule Criteria

Aiming for timely completion of the project, the Panel should compare milestones relating to design, engineering and industrialization for each of the two technologies being considered.

Cost Criteria

The Panel will need to know if there is a significant cost differential between the two designs being examined for completing the 500 GeV project and possibly any upgrades set forth in the ILC Parameters Document. The cost information should be based on available estimates as well as on the Panel's judgments as to the reliability or completeness of the cost estimates. The Panel needs to decide what items are to be included in the cost estimates in arriving at its own comparative analyses.

Report of the Panel

Unanimity in the Panel's recommendation is highly desirable in order to establish the firmest foundation for this challenging global project.

The Panel is urged to report its recommendation as soon as possible, with a firm deadline by the end of 2004.

A full written report with the Panel's evaluation of each of the technologies considered should be available as soon as possible after the Panel's deliberations have been concluded.

The making of the technology choice is a key event in the world particle physics program and thus timeliness in the Panel's reporting is of prime importance. The science agencies need to see a demonstration of the particle physics community's determination and ability to collaborate and to unite around the technology chosen by the Panel, as a trigger for their efforts to collaborate in forming a global project.

Operation of the Panel

The ILCSC would like to make some suggestions regarding procedure.

The Accelerator Sub-committee of the ILCSC is prepared to give an extensive tutorial on the LC. This would inform the Panel about LC issues and acquaint it with the experts from whom they can solicit advice.

Following that, visits to the major LC technology sites, in as close a sequence as possible, would help to solidify understanding of the status and issues while allowing the Panel to receive input on each technology.

To afford the Panel access to expert advice when needed, the ILCSC Accelerator Sub-committee should be in session on site at the Panel meeting place during their meetings.

It is expected that the presentation sessions will be open to the scientific and funding agency communities.

Appendix C

Agenda – Meeting 1

Rutherford Laboratory

January 27-28, 2004

Tuesday 27 January

Morning (9:00 – 12:30) – Meeting of the Panel, including:

- Discussion on how to organize the panel's work
- Presentation of the ITRP charge – Maury Tigner
- Telephone inputs from the Laboratory Directors & ICFA Chair
- Round table – panelists present issues which they think are key to the ITRP recommendation
- Coffee break in the middle of the morning

Afternoon (13:30 – 18:00) - Tutorials

- 13:30 – 14:30 : Detector related issues – David Miller
- 14:30 - 17:45 : X-band linear collider – Kaoru Yokoya, Tor Raubenheimer
- 15:30 – 15:45 : Tea break

Wednesday 28 January

Morning (9:00 – 13:00) – Tutorials

- 9:00 – 12:15 : L-band linear collider – Reinhard Brinkmann, Nick Walker
- 10:30 – 10:45 : coffee break
- 12:15 – 13:15 : conclusions of the Technical Review Committee report – Gerald Dugan

Afternoon (14:00 – 18:00) – panel discussions

- Development of a plan to meet the charge
- Future meetings (places, dates)
- Tea break in the middle of the afternoon

Agenda – Meeting 2

DESY Laboratory

April 5-6, 2004

Monday 5 April 2004

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- Sem. 4 in building 1b**
1. **Closed session** 9:00-10:30
 - 1.1 Introduction to the visit (15 min, A.Wagner) 10:30-10:45
Tea/Coffee (in 1b, Foyer)

 2. **Hall 3 (building 28,a,b)**
Visit to the overall TESLA installations 11:00-13:00
Poster exhibition

 - Lunch in the EXPO/FEL Hall (building 28c)** 13:00-14:00

 - 2.1 **Hall 3 (building 28,a,b)**
Presentations on the spot by experts 14:00-15:45

 - Tea/Coffee (Foyer of the Auditorium)** 16:00

 - Auditorium**
 3. Presentations - part 1 16:30-18:00
 - Status of SC Technology L.Lilje (25'+5')
 - Operational experience with TTF H.Weise (25'+5')
 - Status of SC RF accelerators worldwide
 - Experience etc, including TTF H.Padamsee (25'+5')

 4. **Sem. 4 in building 1b**
Restricted session 18:00-19:00
(Panel reviews the information received,
makes a list of questions for the experts)

Tuesday 6 April 2004

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Auditorium

5. Presentations - part 2 9:00-10:20
 Damping Rings W.Decking (25'+5')
 Status of RF Systems S.Choroba (15'+5')
 Interplay between XFEL and LC R.Brinkmann (15'+5')

Tea/Coffee (in 1b, Foyer)

Sem. 4 in building 1b

6. Restricted Session: 10:40-13:00
a) Presentations continued:
 Industrial Fabrication of SC Cavities D.Proch
 Overall Cost Studies D.Trines
b) Meeting with local experts - responses to the questions.

Lunch in the DESY Bistro

Sem. 4 in building 1b

7. Meet TRC Members, and Final closed session. 14:00-open

Agenda – Meeting 3

SLAC
April 26-27, 2004

April 26

- 8:30 Executive session
- 9:00 Introduction – Jonathan Dorfan (15 min)
- 9:15 X-band Linear Collider Introduction and Overview – David Burke (40 + 15 min)

- 10:10 Coffee Break

- 10:30 NLC Luminosity and Accelerator Physics – Tor Raubenheimer (40 + 15 min)
- 11:25 RF System Overview – Chris Adolphsen (40 + 15 min)

- 12:20 Lunch in ROB

- 1:00 Tour (2 hrs 15 min)

- 3:15 Return to ROB/coffee break

- 3:30 Industrialization and Cost – John Cornuelle (30 +15 min)
- 4:30 LC Commissioning, Operations, and Availability – Tom Himel (20 +10 min)
- 5:00 Summary – Jonathan Dorfan (30 min)

April 27

- 8:00 Executive session
- 8:30 Meet the cold and warm experts
- 9:15 Visit PPM klystrons
- 10:15 Meet local TRC members
- 10:45 Presentation on the Availability Design and Specification from the U.S. Linear Collider Technology Options Study - Tom Himmel (60 min)

- 13:00 Closed Session Telephone Conference with the SLAC Machine Advisory Committee Chair
- 13:45 Civil Engineering and Safety - Vic Kuchler
- 14:00 Beam Energy Stabilization and Long-Term Reliability - Chris Adolphsen
- 14:30 Industrialization and Cost : Day 2 Follow-Up : John Cornuelle
- 15:00 Executive session

Agenda – Meeting 4

KEK

May 25-26, 2004

Scientific Program, Day 1, May 25, 2004

8:30 - 9:00

Closed session

9:00 - 9:15

Welcome Address - Yoji Totsuka

9:15 - 10:00

X-band Linear Collider Overview - Nobu Toge

Break

10:30 - 11:15

Status and Prospects for RF Technologies - Yong Ho Chin

11:15 - 12:00

Status and Prospects for Test Facilities - Hitoshi Hayano

Lunch

13:00 - 13:45

Facilities, Manufacturing Industrialization and Cost - Atsushi Enomoto

14:00 - 17:30

Posters and Tour

Building 3 -- RF development, Site studies, Industry contributions

Assembly Hall -- ATF and GLCTA

AR-South Hall -- RF Power Source Testing

17:30 - 18:00

Prospects of Accelerator-based Science and Technology in Asia – Won Namkung

18:00 - 18:15

Closing Address - Yoji Totsuka

Scientific Program, Day 2, May 26, 2004

8:30 - 12:30

Closed session

Lunch

13:30 - 14:30

Presentation on C-band Collider developments - Hiroshi Matsumoto

14:30 - 18:30

Closed session

Agenda – Meeting 5

Caltech
June 28-30, 2004

Day 1 (Monday, June 28)

8:30 - 10:30 CLIC Presentation (J-P Delahaye and I. Wilson).

10:30 - 11:00 break

11:00 - 13:00 Meeting with the U.S. cold technology proponents.

Presentations by : Steve Holmes (FNAL),
 Christoph Leemann (JLab),
 Hermann Grunder (Argonne).

Lunch break

14:00 – 16:00 TESLA update :

- TESLA: Status and Perspectives (Nick Walker)
- Dark Current (Carlo Pagani)
- Synergy XFEL/LC (Reinhard Brinkmann)
- Comments concerning DESY and TESLA : (Albrecht Wagner)

16:00 – 16:30 break

16:30 – 18:30 Detector and Physics Issues :

Energy Spread Issues : Tim Barklow
Crossing Angle : Philip Bambade
Bunch Timing from the Cold Perspective : Klaus Moenig
Bunch Timing from the Warm Perspective : Hitoshi Yamamoto

Day 2 (Tuesday, June 29) and Day 3 (Wednesday, June 30)

8:30 – 18:00 Closed Sessions.

Agenda – Meeting 6
Korea
Pohang : 11-12 August, 2004
Gyeongju : 13 August, 2004

Closed Sessions.

Appendix D

Questions to Proponents

A. Common LC technology comparison related questions

- 1) Please analyze for us the prospects and problems associated with achieving the parameter goals outlined in the report of the Parameters Subcommittee of the ILCSC.
- 2) Describe the methods for measuring the luminosity profile with energy, absolute beam energy and polarization to the specified precision.
- 3) Are the klystrons now developed sufficiently to power the LC in an efficient way at full energy? What further development is necessary? What margins are needed for adequate performance in the number of spares, MTBF, delivered power, pulse shaping? What is required for breakdown recovery, repair and replacement procedures?
- 4) Describe the tests and simulations needed to demonstrate that the couplers between waveguides to the linac vacuum within structures or cavities will be sufficiently robust.
- 5) How will the low level rf systems required for bunch compression, cavity tuning, machine protection, etc. be designed so as to perform reliably enough not to compromise machine operation?
- 6) Describe the positron production design, and detail the measurements and simulations needed to establish the mechanical, thermal designs and the system reliability. Describe the reasons for your particular choice and the advantages and disadvantages.
- 7) Describe the steps in the scheme to align the rf structures/cavities, quadrupoles, BPMs, and beam delivery elements needed to obtain the *ab initio* gold orbit and subsequent corrections on the time scale of intrabunch train, train to train, and slower time scales from seconds to days. What tests assure that this procedure will work and what R&D remains? Describe the time requirements for the tuning procedures and distinguish between intercepting and non-intercepting techniques.
- 8) Evaluate the electron-cloud effects for the positron beam in damping ring, bunch compressor, linac, and beam delivery system. Is there an R&D plan to cure them?
- 9) What demonstration can be offered now, or during the R&D phase, that the damping rings design is robust with respect to space charge induced emittance growth, fast kickers, the x-y emittance coupling and emittance growth limitation. What estimates for loss of beam availability can be made? Describe the timing requirements for the tuning procedures.

- 10) What are the most severe radiation damage (to electronics or machine elements) issues, and how will they be mitigated? Describe the machine protection system and the studies needed to demonstrate its effectiveness? Describe the analysis of probabilities for catastrophic beam loss.
- 11) Describe how the effects of power supply failures on integrated luminosity will be mitigated.
- 12) Describe the way that vacuum failures in the linacs will be controlled so as not to compromise machine operation or cause damage to sensitive components. What is the impact from repairs that require bringing major sections of the linac to atmospheric pressure?
- 13) Describe the steps needed to operate the LC for precision electroweak measurements at 90 (or 160) GeV with the necessary control of beam energy calibration and stability. What special hardware modifications are needed? What luminosity may be expected? What setup time is required to change from high to low energy operation?
- 14) What is the time estimated to change the energy and re-establish stable operation by steps of ~1% (threshold scan), a few%, or more than 10%?

L-band specific questions

- 15) How can the R1 cryomodule test issue be addressed without the full cryomodule availability at this time?
- 16) What evidence can be given that the 2.5 km cables for transporting high-voltage pulses from moderators to klystrons will provide adequate repairability and reliability?
- 17) How will the TESLA cryogenic systems be controlled to avoid loss of luminosity or component damage?

X-band specific questions:

- 18) Detail the status of the rf structure design and testing. What vulnerabilities still exist for structure damage that could limit the useful life of the accelerator complex. What further studies of the structures are needed to arrive at an engineering design?
- 19) Detail the status of the tests of the full rf delivery system. What vulnerabilities still exist, and how much R&D is required to reach a full technical design.
- 20) The X-band collider has much tighter requirements for the alignment of the beam orbit with the structure axis, yet the basic instrumental precision for alignment is the same as for the L-band collider. The SLC had great difficulty reaching its design luminosity in part because of the difficulty in controlling the beam orbit. How can it be demonstrated that the necessary control of the orbit can be obtained for the GLC/NLC?

B. Cost and Schedule related questions

- 21) Comment on the construction costs and life cycle costs for the two technologies, noting any exceptions or additional information that will help our understanding of the cost comparison.
- 22) What are the reasons and comparisons between one and two tunnel designs for cost optimization, radiation damage, rf system repairs and reliability?
- 23) What is the ratio of the cost increment for raising the energy from 500 to 1000 GeV to the cost of the baseline 500 GeV machine?
- 24) For L-band, provide a modified cost estimation for 500 GeV, assuming 35 MV/m operation and a shorter linac from the beginning. For X-band, provide a modified cost estimation with unloaded gradients 60 and 55 MV/m.
- 25) Delineate the R&D program remaining before a technical design review (TDR) and full cost estimate can be prepared. What are the major projects and the approximate cost of the technical system R&D needed to validate the design.
- 26) Show a technically limited schedule for proceeding to a full TDR, and estimate the schedule for the subsequent linear collider construction. What are the controlling milestones? What are the major technical schedule vulnerabilities?
- 27) Outline the key steps for industrialization of machine components, the likely remaining vulnerabilities in achieving them.
- 28) What is the site power required?
- 29) Provide a technically limited schedule, starting with construction, moving to operation at 500 GeV until 500 fb⁻¹ have been accumulated, and followed by an upgrade to 1 TeV.

C. General LC related Questions:

30) Machine Goals

- Does your technology allow an earlier start to the physics programme, so as to be as concurrent as possible with LHC operation?
 - How do you make the case for determining the final energy choice for the LC prior to LHC results? What if LHC results indicate that a higher energy than design is required?
 - What are the prospects of a luminosity upgrade?
 - Considering that LC will start much later (although it can have concurrent operation period) than LHC, what physics capability does LC have which LHC does not share? Can this be realized at 500GeV or does it require much higher energy?
- 31) Does your technology offer a higher probability of reaching the baseline energy goal earlier, and why? Would your technology allow an easier upgrade path?

- 32) Does your technology offer a higher probability of reaching luminosity goal of acquiring 500 fb⁻¹ within 5 years of turn-on?
- 33) Describe the effect upon your laboratory of a) the warm vs. cold decision, and b) choice of site.
- 34) Discuss the support of the accelerator community for your technology and to whatever extent your technology has outreach into other accelerator areas?