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# STATUS OF THE INTERNATIONAL LINEAR COLLIDER PROJECT*

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Particle physics is entering an exciting time. In the coming years accelerator experiments together with particle and astroparticle physics observations can shed light on many key questions in particle physics and cosmology which are unanswered today. Together with the LHC the ILC will play a crucial role in this respect. This contribution deals with the ILC project comprising physics case, detector studies and accelerator development.

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## 1. Introduction

In the recent years, a broad consensus has emerged in the particle physics community that an $e^+e^-$ Linear Collider, the International Linear Collider (ILC), with a centre of mass energy of up to at least 400 (500) GeV, upgradeable to about a TeV, should be the next big project at the high energy frontier. This consensus as well as the need for a timely realization of the ILC, has been clearly expressed in statements by ECFA, ACFA, HEPAP, ICFA, GSF, and other organizations.

The scientific case for such an accelerator is well described in the document "Understanding Matter, Energy, Space and Time: The Case for the Linear Collider" [1]. It not only indicates the excellent scientific potential of the Linear Collider but also the complementarity, synergy and independence of the different types of colliders, the Large Hadron Collider (LHC) and the ILC:

> Today, particle physics is at the verge of new discoveries. We know with confidence that major discoveries expanding the Standard Model paradigm will occur at the next generation of accelerators. The LHC scheduled to start up in 2007 will take us

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> into the discovery realm. The Linear Collider will extend the discoveries and provide a wealth of measurements that are essential for giving deeper understanding of their meaning, and pointing the way to further evolution of particle physics in the future. The LHC and ILC will offer mutually supporting views of the new physics world at the TeV scale. The interplay between electron–positron and hadron colliders follows a well-established pattern from past research. The $W$ and $Z$ gauge bosons were discovered at a hadron collider, but much of our understanding of their role in the unified electroweak interaction has come from electron–positron collisions. After indirect indications from lepton–hadron and hadron–hadron experiments, the gluons were discovered in electron–positron experiments. Subsequent elucidation of the nature of gluons and their role in quantum chromodynamics came from hadron–hadron, lepton–hadron and lepton–lepton colliders.

In the following, the physics case for the ILC, recent developments on detector R&D and detector design, as well as news on collider design and organizational matters will be presented. Due to the rapid developments in the project described here, mainly links to web pages will be given as references assuming that these will be updated regularly.

## 2. Physics

The physics case for the ILC has been studied and is continued to be studied in all regions, America, Asia and Europe. Results have been published in several reports [2–4] and workshop proceedings [5–7]. The most recent developments can be found on the web pages of the ongoing regional and world wide studies [8]. A nice and comprehensive overview can be found in [9]. A few selected results will be presented below.

Past decades have seen the "discovery" of the Standard Model of particle physics and hadron–hadron, lepton–hadron and lepton–lepton colliders have played crucial roles. Despite its success, the Standard Model, however, is incomplete and leaves many key questions open. Some examples are: What is the mechanism of electroweak symmetry breaking, can all known forces be unified, is there a fundamental symmetry of forces and matter particles, how many dimensions do we live in, what happened at the early universe, what is dark matter and dark energy, and much more.

There are two distinct and complementary roads to gaining more understanding at the energy frontier: High energy and high precision. The hadron collider LHC with its high energy reach will start in 2007, the high precision lepton collider, the International Linear Collider ILC is presently in its design phase and could start at the earliest in 2015. The power of an electron–positron collider lies in its well defined initial state and its relatively clean environment. A first assessment of the physics interplay of the LHC and the ILC can be found in [10]. The LHC experiments have a broad discovery sensitivity, and, beyond discovery, the LHC can perform initial measurements of several properties of the new phenomena. The cleaner environment of electron–positron collisions will be required for a more precise and complete study of most new phenomena discovered at the LHC. It has been demonstrated for essentially every physics scenario beyond the Standard Model involving new particles in the ILC energy range that the ILC results, together with the results from the LHC, can reveal the detailed structure of the underlying physics.

Only with LHC and ILC together the Higgs mechanism can be studied in great detail and could be established as the mechanism responsible for giving mass to the elementary particles. As LEP did allow precision $Z$-boson studies, Higgs studies at the ILC will become precision physics and will allow to look for physics beyond the Standard Model. The studies of the Higgs mechanism would be the first studies of a scalar field ever and could be the very first step towards an understanding of dark energy.

If new phenomena such as supersymmetric particles are observed at the few hundred GeV scale, both accelerators, LHC and ILC, should see some of these new states. However due to the differences of hadron and electron processes, the states seen will be different, and knowledge of those from one program will enhance the studies at the other. Both programs can establish the existence of supersymmetry, but the precision measurements at the ILC will also enable us to understand how it is constructed, and how supersymmetry itself relates to the very high energy scale connected with grand unification of forces or superstrings.

In most scenarios of Supersymmetry, the lightest supersymmetric particle (LSP) lies in the energy range of the ILC. Although invisible and therefore an excellent candidate for dark matter, its properties can be measured at the ILC either when produced together with the next lightest supersymmetric particle which will decay into the LSP plus ordinary particles or, more challenging, through the detection of the photon from initial state radiation when pair produced. In the latter case only a photon will be detected in the detectors and polarization of electrons and positrons is crucial to suppress Standard Model background. The precision studies of supersymmetric particle particle properties at the ILC together with the results from LHC will enable to test unification of gauge couplings or gaugino masses through extrapolation from the weak scale to the GUT scale. Much more information can be found, *e.g.*, in [2] and in the ongoing studies [8] as well as in [10]. These detailed investigations will also allow to establish the LSP as the particle responsible or partly responsible for cold dark matter.

In September 2003, the particle physics community agreed on a parameter list for the ILC [11] based on the physics studies world wide of which only two examples are given above. The baseline machine should cover the entire energy range 200 GeV $< \sqrt{s} <$ 500 GeV, allowing to collect an integrated luminosity of around 500/fb in 4 years with electron polarization of some 80%. The machine should be upgradeable to $\sqrt{s}$ around 1 TeV allowing to collect an integrated luminosity of 1/ab in 3 years. It should be noted here, that the running times given cover only part of the expected program and should be regarded as a measure for the desired availability and reliability of the collider. Several options should be kept open, such as running with a positron polarization of around 50%, high luminosity running at the $Z^0$ resonance and $W$-pair threshold (so-called "Giga-$Z$" option) as well as running as an $e^-e^-$, $e\gamma$ or $\gamma\gamma$ collider. In order to profit most from the synergy of LHC and ILC, concurrent running with the LHC is desired.

In summary, the ILC offers a physics programme of precision measurements and discoveries at the TeV scale and beyond that is well motivated and has been studied in great detail. It has been clearly demonstrated that the results from the ILC will lead to definite conclusions about many features of physics at the TeV scale. Thus, an electron–positron collider in the appropriate energy reach has received great attention and is strongly supported world wide. The physics programme of the ILC is highly complementary to the LHC programme and the synergies arising from the different opportunities at LHC and ILC are presented in [10]. The ILC will, together with the LHC, shed light on key questions like the mechanism of electroweak symmetry breaking, the origin of dark matter and possibly, in a very first step, the origin of dark energy.

## 3. Detector

The high statistical power of the ILC has to be met by an excellent detector performance. High precision measurements demand a new approach to the measurement and reconstruction of events, the reconstruction of as many as possible, ideally all individual particles in an event. The design of the detector has to allow for the best possible exploitation of this particle flow method which requires unprecedented granularity in three dimensions. Research and development on individual detector components is going on world wide. Information on these activities can either be found via the web pages of the world wide [8] and regional studies [12–14] or in the document on International Linear Collider Detector R&D [15]. It should be noted that the development work which was performed for the LHC detectors and the development work ongoing for ILC detectors are complementary in many aspects. The principal challenges at the LHC are related to the high event rate and the high radiation levels associated with the proton collider energies and luminosities required to do physics with the parton component of the proton. The primary requirements for an ILC detector are unprecedented hermeticity, track-momentum resolution, jet-energy resolution and flavor identification for beauty and charm jets. Detector components have to be developed and designed for ultimate precision and very small intrinsic systematic effects. In parallel to the R&D efforts, detector concepts are being developed in order to design detectors optimized for the exploitation of the physics potential of a linear collider.

Best possible jet-energy resolution is required for a detector at the ILC. Unlike at LEP, constrained fits at the ILC are only of limited use, since the initial state is less well defined because of beamstrahlung and since many interesting channels end up in multi-jet final states where fewer constraints are present. Excellent reconstruction of di-jet masses is crucial for example in $WW$ scattering processes or in the process $e^+e^- \to ZHH$ which allows to measures the triple Higgs coupling. Whereas at LEP the best resolution obtained was $60\%/\sqrt{E}$, at the ILC a resolution of $30\%/\sqrt{E}$ is needed. This is well demonstrated, *e.g.*, in [20]. Improving the jet-energy resolution by such a factor of two will yield the equivalent of a four-fold luminosity increase. However, such an improvement puts high demands in particular on the design of the calorimeter. In the following, only some information about efforts in the area of calorimetry will be given.

An ILC calorimeter system should provide the means of reconstructing jet four-momenta. The presently favored method is the particle flow algorithm which relies on the measurement of momenta of charged particles in jets using the tracking system, the energy of photons and electrons using the electromagnetic calorimeter, the energy of neutral hadrons from both the electromagnetic and hadronic calorimeters. The algorithm depends critically on the ability of separating the different components among the energy deposits in the calorimeter. This requires high granularity, both longitudinal and transverse, and the development of particle flow algorithms for different types of calorimeters.

Most efforts in calorimetry for the ILC at present focus on a Silicon–Tungsten electromagnetic calorimeter with cell sizes as small as $1 \times 1\,\mathrm{cm}^3$. However, Lead-Scintillator calorimeters and hybrids of Si–W and scintillators are also considered for cost optimization. For hadronic calorimeters mainly two options are being pursued at the moment. Both are sampling calorimeters with steel plates as absorber material and scintillator or gas chambers as active material. The main difference is, however, the anticipated readout of the active material. Digital readout (for scintillator or gas as active material) allows for a high lateral segmentation with cell sizes as small as $1 \times 1\,\mathrm{cm}^3$. Analogue readout of scintillator cells allows a lateral segmentation down to around $5 \times 5\,\mathrm{cm}^3$. Novel readout devices like Silicon-Photo-Multipliers (SiPM) [16] allow a new and very promising approach to the design of a scintillator based analogue readout hadronic calorimeter [17]. Tests with a large size prototype ($1\,\mathrm{m}^3$ prototype) will be performed. In summary, a large and vibrant R&D program for ILC detectors is ongoing world wide in international collaborations. First results of tests in many areas are very encouraging.

Detector development is supported through the infrastructure project EUDET within the 6th framework of the European Union [18].

## 4. Collider

Many challenges need to be addressed in many areas for a high energy, high luminosity electron–positron linear collider. Concerning energy reach a high accelerating gradient is desirable in order to reach the highest possible energy for a given length. Concerning luminosity high charge densities, very small emittance, tiny beam sizes and long bunch trains with many bunches are needed. In comparison to the SLC, the only linear collider which did run for particle physics up to now, there are orders of magnitude to gain in many aspects, of which a few examples are given here. The centre-of-mass energy should increase by a factor of ten (going from 90 to 1000 GeV), the horizontal spot size needs to be decreased by a factor of hundred (from 500 nm down to 5 nm) and the luminosity must be increased by a factor of 10,000 to a value of $3 \times 10^{34}/\mathrm{cm}^2/\mathrm{s}$. Two accelerating technologies have been developed during the past decades in order to meet these challenging tasks, one based on normal conducting Cu-cavities, the other one based on superconducting Nb-cavities.

Early 2004, the International Committee for Future Accelerators (ICFA) established the International Technology Recommendation Panel (ITRP) to evaluate the two technologies and to recommend a single choice on which to base the linear collider. In its report [19], the ITRP stated that both technologies have been developed to such an extent that both could be used to successfully realize the proposed linear collider. The committee recommended that the linear collider be based on the superconducting rf technology in the clear understanding that the recommendation is on the technology, not on the design itself. This recommendation was based on considerations like the following:

— The large cavity aperture and long bunch interval simplify operations, reduce sensitivity to ground motion and permit inter-bunch feed back.

— The main linac and rf systems are of comparatively lower risk.

— The construction of the superconducting XFEL free electron laser (as a European facility at DESY in Hamburg) 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.
The ITRP recommendation was accepted by ICFA at the Lepton–Photon-Symposium in Beijing in August 2004 and the project was named International Linear Collider ILC.

A crucial role in establishing superconducting rf technology for the linear collider was played by the TESLA Collaboration [20], comprising some 55 institutes in twelve countries. This collaboration achieved major progress during the past decade, such as a 25-fold improvement in performance over cost ratio for superconducting cavities. Gradients of 25 to 35 MV/m are obtained routinely today and values beyond 50 MV/m have already been reached. This technology has already, and will continue to have, major impact on other fields like the next generation light sources or proton accelerators. Development of the superconducting technology is continued within this collaboration, now named TESLA Technology Collaboration.

The choice of technology was expected to enable the project to move forward rapidly with the engagement of both, warm and cold proponents. The range of systems needing attention and novel design approaches from sources to the final focus at the experimental area and finally to the beam dump is so extensive that an optimized design needs pooling of the expertise of all experts world wide. The first meeting of participants in this effort after the technology decision was taking place in November 2004 at KEK in Japan [21]. A lot of enthusiasm, willingness to self-organise and a strong sense of initiative characterized that meeting and helped to advance the global collaboration on well defined work packages and marked this event as a first milestone towards the realization of the ILC. A global R&D and design effort (GDE) is now underway to produce a global design report for the ILC.

The second milestone on the way to the ILC was the 2005 International Linear Collider Workshop (LCWS05) at Stanford University in March 2005 [7]. At that workshop, the director of the Global Design Effort (GDE) was announced. Meanwhile the regional directors (America, Asia, Europe) have also been nominated and the design team comprises some 50 members [22], corresponding to some 25 full time equivalent persons. The GDE is a virtual organization without a specific site. Regular meetings of funding agencies follow and support the ongoing development.

The next crucial step towards a baseline design of the ILC was the meeting of physics, detector and accelerator experts in August 2005 at Snowmass (USA) [23]. The technology driven time line for the ILC foresees a Baseline Configuration Document (BCD) at the end of 2005 and a great deal of progress had been accomplished at the Snowmass workshop. The BCD has meanwhile be published as foreseen [24]. It will be followed by a Reference Design Report (RDR), due end 2006, which will contain already a first cost estimate. A Technical Design Report (TDR) with a detailed cost evaluation is planned for 2008/9. Construction could start around 2010 with commissioning of first beams around 2015. Site selection could happen any time between the publication of the BCD and the start of construction, depending on many different criteria.

European participation in the global design effort is strong as can be deduced from the list of the GDE members [22]. It happens through the involvement of individual institutes and laboratories as well as through combined efforts within the 6th framework of the European Union. The CARE [25] and EUROTeV [26] projects play important roles in this respect. The involvement of the DESY laboratory is in addition characterized by exploiting the synergy between the ILC and the European XFEL project [27] as an approved project to be built near Hamburg. Both projects are based on superconducting rf technology and many developments within the XFEL project are relevant to the ILC as well. In particular the industrialization of many components for the XFEL and the experience with the VUV-FEL (TESLA Test Facility) at DESY will give invaluable experience to the ILC.

## 5. Summary

The scientific case for a Linear Collider in the energy range between 90 and about 1000 GeV is strong and convincing. In synergy with the LHC it will shed light on key questions of particle physics and cosmology like the origin of electroweak symmetry breaking, the origin of dark matter and possibly, in a very first step, the origin of dark energy. The ILC and the LHC offer complementary views of Nature at the energy frontier. A world wide consensus exists on the importance of the ILC and on its timely realization. Detector technologies and detector concepts are being developed to exploit this physics potential. The superconducting technology for the ILC is well developed, the design of the collider is well on track for a starting date for commissioning in 2015, a date which is technologically possible. Together with the LHC, the ILC can provide an exciting and promising future for discoveries and for understanding the universe and its origin.

I would like to thank the organizers very much for this pleasant and exciting workshop.

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