The International Linear Collider

Ties Behnke*

DESY, Notkestrasse 85, 22607 Hamburg, Germany

Received 19 February 2010, accepted 19 February 2010

Published online 30 March 2010

Key words Linear collider, ILC, detector development, ILD.

A high energy electron positron collider is proposed to complement the large hadron collider, LHC, which has started taking data at CERN, Geneva, Switzerland. Based on superconducting acceleration technology the International Linear Collider ILC is offering a mature proposal. It will deliver high luminosity electron positron collisions at 500 GeV upgradable to 1 TeV. Experimentation at such a collider presents many unique challenges, if the huge physics potential should be harvested efficiently. In this paper after a brief review of the state of the accelerator proposal the state of the preparation of the experimental program is discussed.

© 2010 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

1 Accelerators at the energy frontier

Particle physics is about to enter a new phase, the phase of physics at the Terascale. The first accelerator to directly explore this new regime will be the large hadron collider at CERN. First collisions to the experiments were delivered in 2009, routine operation, although at a somewhat reduced energy of 7 TeV, is expected for 2010. Within a few years the LHC will shed light on the physics present at these very high scales. It seems nearly certain that the LHC will be able to answer the long standing Higgs puzzle - is there a light Higgs or is there not. New physics, of which many different types have been predicted for these energies, will become apparent after relatively short running periods.

The large hadron collider collides protons with protons, which allow it to reach very high energies in a machine of reasonable size. The analysis of the events however is complicated due to the presence of the underlying event, and by the fact that the initial conditions of the hard collision are not well known. In particular for precision measurements this limits the reach of the LHC.

To fully understand the physics at these high scales, the discovery potential of the large hadron collider needs to be complemented by the precision possible with an electron positron collider. Here point like particles with no substructure are collided, with well defined initial conditions. This allows an experiment at a high luminosity electron positron collider to do precision measurements of many phenomena.

In the past hadron and lepton collider have very fruitfully worked together to explore and to investigate the physics at ever larger energy scales. The most recent example is the very positive cooperation and interference between LEP and the Tevatron, which added significantly to our understanding of the electroweak physics in particular.

At the moment two projects for lepton colliders are followed: for a collider at energies up to 1 TeV the mature ILC proposal exist [1]. Should higher energies be needed the CLIC technology is being developed under the leadership of CERN [2]. CLIC promises to reach energies up to 3 TeV in a facility of a similar footprint as the ILC. The technology however is less advanced than the ILC technology, and a convincing proof of principle of this very exciting proposal is still missing. A more detailed discussion of the CLIC proposal can be found in a separate contribution to this proceedings.

* E-mail: ties.behnke@desy.de, Phone: +494089984918

There are a number of parameters which can be optimized to get the highest possible luminosity. The central relation is the equation relating the luminosity with beam parameters

$$\mathcal{L} = \frac{n_b N^2 f_{\text{rep}}}{4\pi\sigma_x\sigma_y} H_D \quad (1)$$

where n_b is the number of bunches in a train, N the number of particles per bunch, f_{rep} the repetition rate of the bunch trains, σ_x, σ_y are the transverse beam sizes, and H_D is the disruption parameter. With given overall machine parameters a key parameter to increase the luminosity are the beam sizes. At a linear collider, where beams interact only once, one can afford to push very hard on the beam sizes. As the beam sizes become very small the interaction between the two bunches becomes very large, to the point that the beams eventually destroy themselves by radiating large amounts of energy. This energy lost by this so called beamstrahlung is parametrized by

$$\delta_{BS} = \frac{er_e^3}{\sigma_z} \left(\frac{E_{cms}}{\sigma_z} \right) \frac{N^2}{(\sigma_x + \sigma_y)^2} \quad (2)$$

where σ_z is the length of the interaction region, σ_x and σ_y are the beam sizes in transverse direction. A simultaneous optimization of the luminosity and beamstrahlung loss at the same time favours a flat beam geometry, where one of the transverse dimensions is much smaller than the other. Typical numbers for the ILC are 500 nm in x , and 5 nm in y .

The international linear collider ILC is a design of a collider based on superconducting accelerating cavities. The superconducting technology has been selected because the technology is mature and well understood. A collider built with superconducting cavities can be operated at relatively low RF frequencies, which translate into large apertures for the beam, and benign alignment tolerances along the accelerator. The transformation of electrical energy into luminosity is efficient.

Fig. 1 (online colour at: www.fp-journal.org) Schematic layout of the ILC facility.

The parameters of the international linear collider, ILC, have been chosen to deliver high luminosity collisions at energies between 90 GeV and 1 TeV. In its first phase the maximum energy will be 500 GeV, with an luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ or an integrated luminosity of 500 fb^{-1} for the first three years. Collisions happen in trains of a few thousand bunch crossings. Within the train, bunches are separated by 370 ns, for a full bunch train length of 1 ms. Bunch trains are repeated with a frequency of approximately 5 Hz. A schematic layout of the facility is shown in Fig. 1.

2 The physics program of the ILC

Running at an energy of around 500 GeV, the ILC will increase the energy in an electron-positron collider compared to the last running facility, LEP II, by about a factor of 2.5. It will be a $t\bar{t}$ factory, producing large samples of this particle, and allow studies of top physics with unprecedented precision. Samples of the

heavy electroweak bosons, W and Z , a focus of the program at the LEP collider, will be present in large numbers, and might still present some surprises if studied in detail.

A major focus of the studies at this collider will be the Higgs particle or whatever equivalent nature has in stock. From current precision measurements in the electroweak sector a light higgs particle with a mass around 120 GeV seems favored. At the ILC essentially all quantum numbers of the Higgs will be accessible, allowing a complete picture to be obtained of this most elusive of all currently known or anticipated particles. The mass and width of the Higgs will be measured with great precision, as will be its branching ratio into all known fermions. In particular this measurement will be central in experimentally establishing the Higgs mechanism in its core property, the coupling proportional to the mass of the involved fermions. If enough data can be collected even one of the most difficult measurements in the Higgs sector, the measurement of the coupling of the Higgs to itself, might be possible. Together these measurements will allow a complete test of the Higgs sector, and thus an in-depth probe of the standard model in this unexplored region. Even though the higgs particle will have been discovered by the LHC by the time the ILC might start taking data, the complete exploration of the higgs section will be left to a lepton collider.

Many physicists expect that the standard model is only an effective low-energy theory of a more complex and rich theory. A very popular extension of the standard model is supersymmetry, which predicts many new states of matter. If supersymmetry exists, the LHC has an excellent chance to find it - or something similar. As long as the masses of the supersymmetric particles are within reach of the linear collider, a rich field of study opens up for the ILC. The ILC will be able to study the particles and their decays in great detail, and with great precision. Because of the richness of the theoretical possibilities of supersymmetry and similar theories, an experimental decision which theory is right or wrong will require many measurements and detailed exploration of the structures of the theory. We will have to wait for the combination of the large discovery reach of the LHC with the precision measurements possible at the ILC before final conclusions can be drawn.

But running at these high energies the ILC will also simply be open for surprises. The clean nature of the events, and the possibility to accept nearly any event will make the ILC an ideal discovery machine. Together with the LHC the ILC will enable science to explore the physics at the Terascale and to learn more about the fundamental nature of our world.

By the time a linear collider will turn on the LHC will have been running for a number of years. The phase space for new physics in this energy regime will be significantly reduced, and the interesting energy regime will be much better determined than at the moment. Thus the final parameters of the ILC, in particular its top energy, will be determined only once the LHC results are known. Also only at that time can the final decision be taken if the ILC technology is the right choice, or if a scheme which allows to reach even higher energies like CLIC will be needed.

3 Experimentation at the linear collider

The ILC is a facility which has been designed to address a wide range of physics questions. A detector at this facility has to be a multi – purpose detector, which is capable to look at many different final states, at many different signatures and topologies.

Many of the interesting physics processes at the ILC appear in multi-jet final states, often accompanied by charged leptons or missing energy. The reconstruction of the invariant mass of two or more jets will provide an essential tool for identifying and distinguishing W 's, Z 's, H 's, and top, and discovering new states or decay modes. To quantify these requirements the di-jet mass is often used. Many decay chains of new states pass through W or Z bosons, which then decay predominantly into two jets. To be able to fully reconstruct these decay chains, the di-jet mass resolution should be comparable or better than the natural decay width of the parent particles, that is, around 2 GeV for the W or Z :

$$\frac{\Delta E_{\text{di-jet}}}{E_{\text{di-jet}}} = \frac{\sigma_m}{M} = \frac{\alpha}{\sqrt{E(\text{GeV})}}, \quad (3)$$

where E denotes the energy of the di-jet system. With typical di-jet energies of 200 GeV at a collision energy of 500 GeV, $\alpha = 0.3$ is a typical goal. Compared to the best existing detectors this implies an improved performance of around a factor of 2. It appears possible to reach such a resolution by optimally combining the information from a high resolution, high efficiency tracking system with the ones from an excellent calorimeter. This so called particle flow ansatz [3,4] is driving a large part of the requirements of the ILC detectors.

Typical events at ILC are hadronic final states with Z and W particles in the decay chain. Typically around 60% of all stable particles are charged, slightly less than 30% are photons, only around 10% are neutral long lived hadrons, and less than 2% are neutrinos. At these energies charged particles are best re-constructed in the tracking system. Typical momentum resolutions which are reached in detectors are $\delta p/p \approx 5 \times 10^{-5}$, much better than any calorimeter system at these energies. Typical electromagnetic energy resolutions are around $\delta E_{\text{em}}/E = 0.15/\sqrt{E}(\text{GeV})$, typical resolutions achieved with a good hadronic calorimeter are around $\delta E_{\text{had}}/E = 0.45/\sqrt{E}(\text{GeV})$. Combining these with the proper relative weights, the ultimate energy resolution achievable by this algorithm is given by

$$\sigma^2(E_{\text{jet}}) = w_{tr}\sigma_{tr}^2 + w_{\gamma}\sigma_{\gamma}^2 + w_{h^0}\sigma_{h^0}^2, \quad (4)$$

where w_i are the relative weights of charged particles, photons, and neutral hadrons, and σ_i the corresponding resolution. Using the above mentioned numbers an optimal jet mass resolution of $\delta E/E = 0.16/\sqrt{E}(\text{GeV})$ can be reached. This error is dominated by the contribution from the energy resolution of neutral hadrons, assumed to be $0.45/\sqrt{E}(\text{GeV})$. This formula describes a perfect detector, with perfect efficiency, no acceptance holes, and perfect reconstruction in particular of neutral and charged particles in the calorimeter. In reality a number of effects result in a significant deterioration of the achievable resolution. If effects like a final acceptance of the detector, missing energy e.g. from neutrinos etc. is included, this number easily increases to $25\%/\sqrt{E}$ [5, 6]. The optimisation of the detector and the calorimeter in particular has to be done in a way that these wrong associations are minimised.

From the discussion above it is clear that three effects are of extreme importance for a detector based on particle flow: as good hadronic energy resolution as possible, excellent separation of close-by neutral and charged particles, and excellent hermeticity. It should also be clear that the ability to separate closeby showers is more important than ultimate energy resolution: it is for this reason that total absorption calorimeters, as used e.g. in the CMS experiment, are not well suited for the particle flow approach, as they do not lend themselves to high segmentation.

Existing particle flow algorithms start with the reconstruction of charged tracks in the tracking system. Found tracks are extrapolated into the calorimeter, and linked with energy deposits in there. If possible, a unique assignment is made between a track and an energy deposit in the calorimeter. Hits in the calorimeter belonging to this energy deposit are identified, and are removed from further considerations. The only place where the calorimeter information is used in the charged particle identification is in determining the type of particle: calorimeter information can help to distinguish electrons and muons from hadrons.

What is left in the calorimeter after this procedure is assumed to have come from neutral particles. Clusters in the calorimeter are searched for and reconstructed. With a sufficiently high segmentation both transversely and longitudinally, the calorimeter will be able to separate photons from neutral hadrons by analysing the shower shape in three dimensions. A significant part of the reconstruction will be then the reconstruction of the neutral hadrons, which leave rather broad and poorly defined clusters in the hadronic calorimeter system.

Particle flow relies on a few assumptions about the event reconstruction. For it to work it is important that the event is reconstructed on the basis of individual particles. It is very important that all charged tracks are found in the tracker, and that the merging between energy deposits in the calorimeter and tracks in the tracker is working as efficiently as possible. Errors in this will quickly produce errors for the total energy, and in particular for the fluctuations of the total energy measured. Not assigning all hits in the calorimeter to a track will also result in the creating of additional neutral clusters, the so called double counting of energy.

Fig. 2 (online colour at: www.fp-journal.org) The jet energy resolution, α , as a function of the dip angle $|\cos \theta_q|$ for jets of energies from 45 GeV to 250 GeV.

Reconstructing all particle implies that the number of cracks and the holes in the acceptance should be minimized. This is of particular importance in the very forward direction, where the reconstruction of event properties is complicated by the presence of backgrounds. However small errors in this region will quickly introduce large errors in the total energy of the event, since many processes are highly peaked in the forward direction.

In Fig. 2 the performance of one particular particle flow algorithm, PandoraPFA [6] is shown, as a function of the dip angle of the jet direction, $\cos \theta$. The performance for low energies of the jets, 45 GeV is close to the optimally possible resolution if the finite acceptance of the detector is taken into account. At higher energies, the confusion terms start to be more important. Jets at higher energies are boosted more strongly, resulting in smaller average distances between particles in the jet. This results in a worse separation of particle inside the jet, and thus a worse resolution.

4 Detector optimization

Even though particle flow, as outlined in the previous section, is a core ingredient of the design of a detector at the ILC, other considerations are important as well. An excellent spatial resolution for charged particles is of key importance, both for vertexing and for momentum resolution. Many final states of interest contain heavy flavours, which are tagged using life time information. A particularly challenging channel is the reconstruction into $c\bar{c}$ final state, as it is important e.g. for the investigation of the Higgs boson. The momentum resolution is of particular interest in the reconstruction of the Higgs in the model independent method using the muon recoil mass spectrum. In this case the precision which can ultimately be reached depends on the momentum resolution only.

Several groups have attempted to find an overall optimised detector layout, which satisfies all the discussed criteria. The international large detector, ILD, is one of currently two developed concepts. It is built on the assumption that particle flow is the main reconstruction method, thus having at its core a high granular very powerful calorimeter. Tracking relies on a combination of a large volume gas-filled TPC and a sophisticated system of Silicon detectors both inside and outside the TPC. A schemativ view of the ILD detector is shown in Fig. 3.

5 Summary

A linear collider operating at energies up to 1 TeV is a very powerful and promising facility. Experimentation at such a facility presents many challenges. The novel concept of particle flow is at the core of the detectors proposed for this facility, and has triggered a very ambitious development program for a novel type of calorimeters and detectors. The eventual realisation of the ILC as an international research facility will depend on the physics at the Terascale found by the LHC. This collider is expected to shed first light

Fig. 3 (online colour at: www.fp-journal.org) Three-dimensional image of the proposed ILD detector at the ILC.

on this next energy regime. Based on its findings the energy reach of this new facility will be finally determined. In case that energies above 1 TeV are needed, another technological approach for the collider will be needed, e.g. the CLIC proposal, discussed in a different presentation in this conference. However if the LHC confirms the findings from current high precision experiments which point to a low mass Higgs, and new physics below 1 TeV, the ILC will be the right machine to build to fully explore this energy regime.

References

- [1] ILC Collaboration, ILC Reference Design Report Volume 1 – Executive Summary, edited by J. Brau, Y. Okada, and N. Walker, arXiv:0712.1950.
- [2] S. van der Meer, The CLIC Project and the Design for an e^+e^- Collider, Part. Accel. **30**, 127 (1990).
G. Geschonke, Results from the CLIC Test Facility CTF3 and Update on the CLIC Design, in: the Proceedings of 11th European Particle Accelerator Conference (EPAC 08), Italy, 23–27 June (Magazzini del Cotone, Genoa, 2008).
- [3] J. C. Brient, Improving the Jet Reconstruction with the Particle Flow Method: An Introduction, Proceedings of the 11th International Conference on Calorimetry in High-Energy Physics (Calor 2004), Perugia, Italy, 29 March–2 April 2004, edited by C. Cecchi and P. Cenci (World Scientific, 2005).
- [4] V. L. Morgunov, Energy-flow Method for Multi-jet Effective Mass Reconstruction in the Highly Granulated TESLA Calorimeter, in Proceedings of the APS/DPF/DPB Summer Study on the Future of Particle Physics, Snowmass 2001, edited by N. Graf, In: The Proceedings of APS/DPF/DPB Summer Study on the Future of Particle Physics, Snowmass, Colorado, 30 June–21 July 2001, (eConf c010630, SLAC, Snowmass, Colorado, 2001), pp. E3041.
- [5] P. Krstonsic, Measurement of Quartic Boson Couplings at the International Linear Collider and Study of Novel Particle Flow Algorithms, DESY Thesis-08-007, <http://www-library.desy.de/cgi-bin/showprep.pl?thesis08-007>.
- [6] M. A. Thomson, Nucl. Instrum. Methods A **611**, 25 (2009) [arXiv:0907.3577 physics.ins-det].