Detector Concepts at the International Linear Collider

Ties Behnke

DESY, Notkestrasse 85, 22603 Hamburg, Germany

Abstract

The international linear collider, ILC, is a project for a 500 GeV linear electron positron collider, upgradable to 1 TeV, and also capable of running at energies below 500 GeV. The proposal is optimised for high luminosity and a clean collision environment. Such a machine is ideally suited to do precision studies of the electroweak breaking mechanism, study possible new physics scenarios, and search for new phenomena. It complements the LHC through precision and a well known intial state. Experimentation at such a facility is a major challenge if the potential for precision given by the collider should be optimally utilized. In this article the state of the experimental proposals for the ILC is reviewed.

Key words: International Linear Collider, ILC, Detector Concepts at the ILC, Particle Flow, Time Projection Chamber, Precision Silicon Tracking

1. Introduction

A linear electron positron collider will be the next major facility in the field of particle physics, which will supplement the large hadron collider currently being commissioned at CERN. Experimentation at such a facility offers significant challenges. Over the past few years groups have formed to address these challenges in two ways. Technologically oriented collaborations have formed which develop different technologies in view of their eventual use at a linear collider. These groups pursue ambitious development and test beam programs, and have made huge progress over the last few years. The results of the R&D groups are combined into a detector concept by the concept groups, of which two are currently proposing a detector for the ILC in earnest. These detector concept groups have proposed integrated detector concepts, and push studies to demonstrate the physics reach of the detectors at a linear collider.

In this paper the concepts at a linear collider are reviewed, with a particular emphasis on the fundamental techniques used at a linear collider. After an introduction into the linear collider, the concept of event reconstruction at a linear collider is developed, followed by a discussion of the technologies proposed for the main parts of such a detector.

2. The International Linear Collider

The next major discoveries in particle physics are expected to come from the large hadron collider at CERN, which is starting to record significant amounts of data in 2010. The large hadron collider accelerates protons to eventually 7 TeV per beam, and collides them in four interaction regions. Even though this facility offers by far the largest discovery reach of any facility under discussion or operating, there are many questions which will need an alternative technology, that of lepton collisions. Colliding leptons offer a number of significant advantages, since the initial state is well known, the collision energy of the fundamental constituents is well determined, and there is no underlying event which confuses the picture.

The main drawback of a lepton collider is the more limited energy reach compared to a hadron collider. LEP2, the electron - positron collider which operated at CERN until the year 2000, reached an energy of 200 GeV in a ring of 27 km circumference. The energy lost by synchrotron radiation increases with the fourth power of the energy of the beam, which very quickly makes the operation of a circular lepton machine prohibitively expensive. A collider at a centre of mass energy of 500 GeV would need, if realized as a circular collider, a tunnel with a circumference exceeding 100 km, which is clearly excluded. The only alternative is the construction of a linear collider, which however is very challenging in terms of reaching the required acceleration gradient, and in terms of reaching the required high luminosity.

Over the last ten years a number of different proposals for linear accelerators have been investigated. In 2005 the international community decided to concentrate on the superconducting technology as the most promising road to realize a linear collider quickly. This technology is well suited for a collider of energies up to 1 TeV. A facility with a footprint of around 30 km could house the baseline machine, a collider with a top energy of 500 GeV. An upgrade to higher energies requires more tunnel length. The international linear collider, ILC, is a concrete proposal based on the superconducting technology, for a 500 GeV collider, upgradable to 1 TeV. It is designed to reach a peak luminosity of $2 \times 10^{34} cm^{-2} s^{-1}$, or an integrated luminosity of 500 fb^{-1} over 3 years . A complete and costed conceptual design of the collider has been presented in 2007 [2], a technical design is expected for 2012. A view of the ILC facility is shown in fig 1.

Although the current work concentrates on the design of a

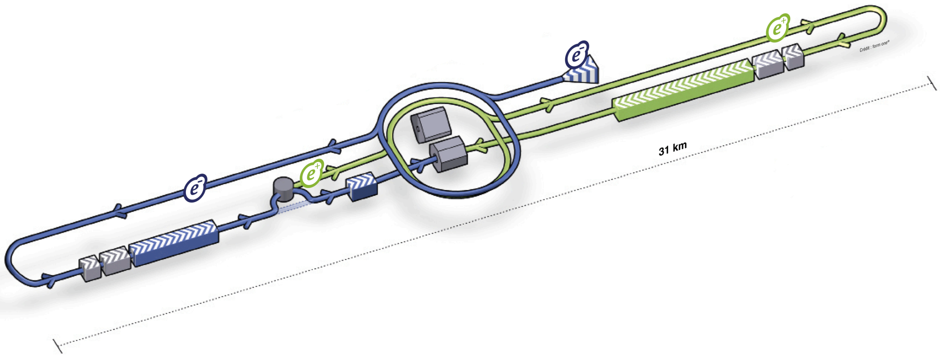

Figure 1: Artists view of the ILC facility, showing the main components, and giving an indication of the site dimensions.

500 GeV machine, the exact parameters, including the final top energy, will depend on the findings of the LHC. Indirect evidence from different experimental results point to the existence of a light higgs boson, at a mass below 200 GeV, and hint at the existence of light supersymmetry or a similar extension of the standard model. If this scenario is found by the LHC, or of parts of this are found, the ILC is the right machine to build, and the energy reach of the facility below 1 TeV is appropriate.

If the LHC finds that a very different scenario is realized in nature, and that significantly higher energies are needed, the CLIC technology becomes interesting. CLIC is a proposal for a very different acceleration scheme, pursued mostly by CERN [3]. At CLIC a low energy high current electron beam produces the RF needed to accelerate a parallel low current high energy electron or positron beam. The accelerating structures are normal conducting, and are expected to reach acceleration gradients up to 100 MV/m. A facility of close to 50 km length could then reach a top energy of 3 TeV, which more or less coincides with the discovery reach of the LHC running at 14 TeV. Currently the CLIC technology has not yet been proven to work reliably. The main problem is frequent breakdowns in the acceleration structures, which make an efficient acceleration impossible. Work is ongoing to improve this, and to demonstrate the feasibility of this technology by 2012. Since CLIC is a normal conducting machine, it has to operate at high RF frequencies, current planned to be 11 GHz. This translates into very tight alignment tolerances of the machine, at least an order of magnitude stricter than in the case of the ILC.

The key parameters of the two collider concepts are summarized in table 1.

In the following the discussions of the physics case and of the proposed experiments will concentrate on the international linear collider, as the most mature project, which could be built today.

3. Physics at the ILC

The physics case for the linear collider has been developed over a number of years, and is well documented in a series of documents, for example [1, 2]. While precision studies of standard model particles, like the top, the Z and the W, or B, play an important role, the real justification comes from new physics as e.g. the higgs, or supersymmetry, or others.

A strength of the lepton collider is the potential for precision studies. A prime example is the higgs sector. The particle will most probably be discovered at the LHC, if it exists, and if it is at a "'reasonable"' mass, so that it can still be considered as a real particle. To establish the higgs mechanism, all relevant quantum numbers have to be measured. This will be very difficult, if not impossible, at the LHC, while it is well possible at a linear collider.

The same is true for nearly any scenario on new physics, as long as it is within reach of the linear collider. The determination of absolute branching ratios, and the precise measurement of masses, will only be possible at a lepton collider.

If the higgs boson is light, it will be produced predominantly in the higgs strahlungs process, accompanied by a Z boson. In this case the analysis of the decay of the Z completely determines the properties of the higgs, without ever needing to detect the higgs itself. This so-called higgs-recoil method allows a completely model independent investigation of the properties of the higgs, and will be a mainstay of the higgs analysis.

Due to the clean nature of the events, the reconstruction of the higgs decays into a wide variety of different particles will allow the detailed investigation and the final experimental establishment of the higgs mechanism. If enough event can be collected, the measurement of the self coupling of the higgs might even be possible [4].

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 super symmetric particles

		ILC	CLIC
Parameter	Unit	Value	
Center-of-mass energy	GeV	200-500	3000
Peak luminosity	$cm^{-2}s^{-1}$	2×10^{34}	$1.5 - 5.9 \times 10^{34}$
Pulse Rate	Hz	5	50
Pulse Length	ms	≈ 1	156×10^{-6}
Number of bunches / pulse		$1000 - 5400$	312
Time between bunches	ns	$1000 - 185$ 0.5	
Beam size (horizontal) at IP	nm	639	40
Beam size (vertical) at IP	nm	5.7	1
Bunch length at IP	μm	300	
Electron Polarization	%	> 80	
Positron Polarization (optional)	%	> 60	
Site length	km	40	48.3

Table 1: Some basic design parameters of the ILC and CLIC (3 TeV option) accelerators.

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.

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.

The physics program of a lepton collider running at energies above 1 TeV will strongly depend on the findings at the LHC. Many of the measurements discussed in the contact of the ILC facility will also be possible at a CLIC facility. The precision of many of these studies will depend on the capability of CLIC to run at energies below 1 TeV. In addition CLIC will be sensitive to new states of higher mass.

4. Detector Concepts at the ILC

Experimentation at the ILC is very challenging. Contrary to the LHC, where radiation hardness if of prime concern at least for the inner detectors, this is not critical at the ILC. Optimizing the detectors for precision physics is possible and is required if the potential of the collider should be optimally exploited.

The experiment at the ILC operates in an environment where a train of bunches of about 1 ms in length is followed by a long quiet period of close to 200 ms, needed for the RF cavities to be recharged. Within one train bunches are spaced at approximately 350 ns maybe twice as much in the latest version of the machine. This peculiar bunch structure has two consequences: to fully optimize the events, local buffering of the information is needed, to cover one train, but then a lot of time exists to readout the buffers, and prepare the detector for the next train. Indeed, to save power and thus limit the cooling requirements, the time between trains is long enough that a big part of the front end electronics can be switched off, or put into a standby power-saving mode, reducing the duty cycle of the readout to a few percent. This has a large impact on the design of the electronics, but offers large advantages by significantly reducing the average power dissipated inside the detector, and thus the need for active cooling.

At nominal luminosity the probability to observe more than one collision per event is very small. The only significant source of physics background is from $\gamma\gamma$ events, which produce mostly forward going particles. To fully utilize the luminosity no hardware trigger in the conventional sense is foreseen. Every collision is recorded, and a selection between interesting and less interesting events will happen offline, in software. This trigger less operation seems well possible with the expected rates of collisions and background.

A detector at the ILC is designed as a traditional multipurpose detector, which provides hermetic coverage for neutral and charged particles. The momentum of charged particles is measured in a strong magnetic field, aligned parallel to the beams.

A focus of the physics at the ILC will be the reconstruction of hadronic final states. Jet physics therefore is very important, and the capability of the detector to measure jet masses becomes paramount. Many final states involve the heavy gauge bosons W and Z, and the reconstruction and separation of the W and Z masses is one frequently used gauge to quantify the performance of the detector. 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:

$$\frac{\Delta E_{di-jet}}{E_{di-jet}} = \frac{\sigma_m}{M} = \frac{\alpha}{\sqrt{E(\mathrm{GeV})}}, \tag{1}$$

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.

Many final states of interest contain long lived particles, e.g. b-quarks. Even more challenging is the tagging of charm quarks, or the determination of the quark charge in jets. Tagging these is a key requirement of a detector. An excellent vertex detector is therefore necessary.

Over the past years several groups have formed which have developed integrated concepts for a detector at the linear collider. In 2009 an international advisory group has reviewed the state of the different concept groups, and has validated two detector concept groups as being advanced enough to continue towards an engineering design of a detector. Both, the international large detector, ILD [5] and the Silicon Detector, SiD [6] are modern multi-purpose detectors, which combine excellent vertexing and tracking with advanced calorimeter concepts. In the following the design criteria and the technological options will be described in more detail. A 3-dimensional view of one of these concepts is shown in Figure 2.

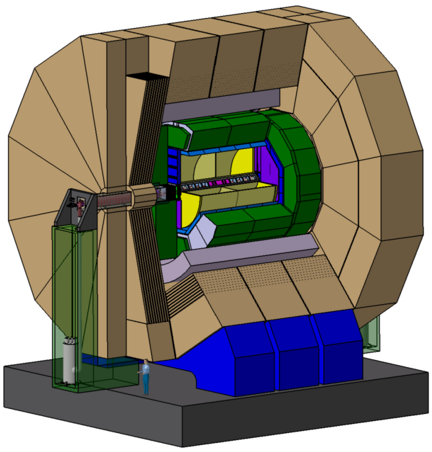

Figure 2: Three-dimensional image of the proposed ILD detector at the ILC.

4.1. Particle Flow

As discussed above the precise measurement of jet-masses is a key requirement for a detector at the ILC. The currently most favored procedure to obtain the optimal resolution is the so-called particle flow ansatz. In this procedure, information from all subdetectors is combined in an optimal way to reconstruct every individual particle, both charged and neutral.

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. The charged particles are best re-constructed in the tracking system. Typical momentum resolutions which are reached in detectors are $\delta p/p^2 \approx 5 \times 10^{-5} GeV^{-1}$, much better than any calorimeter system at these energies.

Typical electromagnetic energy resolutions are around $\delta E_{em}/E = 0.15/\sqrt{E}(\mathrm{Ge}V)$, typical resolutions achieved with a good hadronic calorimeter are around $\delta E_{had}/E = 0.45/\sqrt{E}(\mathrm{Ge}V)$. Combining these with the proper relative weights, the ultimate energy resolution achievable by this algorithm is given by

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

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 $d\delta E/E = 0.16/\sqrt{E}(\mathrm{Ge}V)$ can be reached. This error is dominated by the contribution from the energy resolution of neutral hadrons.

These considerations are valid for 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 finite acceptance of the detector, missing energy e.g. from neutrinos etc. is included, this number easily increases to $25\%/\sqrt{E}$ [7, 8]. All this assumes that no errors are made in the assignment of energy to photons and neutral hadrons in particular.

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 obvious that the ability to separate close by 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. The assignment of calorimeter clusters to charged hadrons is particularly challenging. Sophisticated clustering algorithms have been developed which try to identify the hadronic shower, and try to even merge outlying fragments with the original core of the shower. The clustering relies heavily on topological information, and thus stresses the spatial resolution of the calorimeter.

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 analyzing 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 charged particles are found in the tracker with very high efficiency, 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 to the total energy, and in particular to the fluctuations of the total energy measured. Not assigning all hits in the calorimeter to a track will also result in the creation of additional neutral clusters, the so called double counting of energy.

Reconstructing all particles implies that the number of cracks and the holes in the acceptance should be minimized. A particular difficult region in the detector is the very forward region. Here the measurement of charged particles is worse, since particle will fly mostly in the direction of the magnetic field, and thus the momentum resolution will become worse very rapidly. For particles in the very forward region backgrounds from beam beam interactions start to become important as well, which will increase the number of background hits in both the tracker and in the calorimeter, and make an assignment track - calorimeter worse. In addition the amount of material between the tracker and the calorimeter is typically significantly larger in the forward region than it is in the barrel region of a detector. For the ILD detector concept, which relies on a TPC as central tracking detector, the amount of material increases from less than 5% in front of the calorimeter in the barrel region to 20% or more in the forward region. This dead material will produce a large number of photons from interactions in the material, which will introduce additional sources of confusion.

Over the past years several algorithms have been developed which try to implement particle flow for a detector at the linear collider. The central part of these algorithms is an efficient clustering algorithms, and a good way to connect charged particle tracks with clusters in the calorimeter.

In Figure 3 the performance of one particular particle flow algorithm, PandoraPFA [8] 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 particles start to overlap, and the reconstruction starts to pick up errors in the assignment between tracks and clusters. This effect, called confusion, will deteriorate the resolution, and will become more important at higher energies.

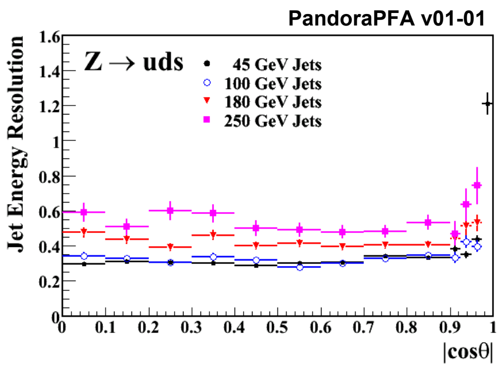

Figure 3: The jet energy resolution, α, as a function of the dip angle $|\cos\theta_q|$ for jets of energies from 45 GeV to 250 GeV.

4.2. *Overall layout of a detector at the ILC*

The detector concepts at a linear collider are typical multipurpose detectors similar to the ones recently built for the LHC. A collider like the ILC allows the vertex detector to be installed rather close to the primary interaction vertex. At the ILC the first layer of the vertex detector is located at 15 mm, which allows an excellent reconstruction of secondary vertices. In the ILD detector a large volume time projection chamber serves as the main tracking device. It is supplemented by two layers of silicon strip detectors in-between the vertex and the TPC, and a layer of silicon strip detectors outside the TPC. In the forward direction, close to the beam pipe, silicon disks, partially realized as pixel detectors, partially realized as strip detectors, close the acceptance gap below the TPC acceptance.

In the SiD detector concept five layers of silicon strip detectors replace the time projection chamber for an all silicon tracker, similar to the tracker of the CMS detector. A system of barrel detectors and end cap disks will complete the solid angle coverage.

Outside the tracker a highly segmented calorimeter serves as a central detector piece to make particle flow reconstruction possible. Segmentation in both transverse and longitudinal direction becomes coarser for the rear part of the calorimeter which serves mostly to measure hadrons.

All these components are immersed in a magnetic field which is used to determine the momentum of charged particles. Fields between 3.5 T for ILD, and 6 T for SiD, are used. Even though a large coil is expensive and difficult to built there is no alternative to having both tracker and calorimeter inside the coil, as the material from the coil if introduced between the tracker and the calorimeter would spoil any hopes of attaining the required particle flow performance.

Outside the coil an instrumented iron return yoke serves as a muon detector and tail catcher.

In the very forward direction a small high precision calorimeter close to the beam pipe serves as a luminometer, and closes the gap in acceptance for the electromagnetic calorimeter. At angles below the luminometer, integrated into the beam extraction system, a small and radiation hard calorimeter is installed, which is used to measure the backgrounds, and can also be used in some physics studies to extend the sensitivity for high energy electrons to very low angles.

In the following the main detector systems will be discussed in more detail, and in particular technologies discussed to realize these components will be introduced.

4.3. *Tracking Detectors*

The innermost tracking detector is a high precision pixel detector, which serves primarily as a tool to reconstruct secondary vertices, but which can also - because of its high intrinsic point resolution - contribute to the overall tracking. The main challenge at the ILC is to construct this detector with a minimum of material - goal is less than 0.1% of a radiation length per layer - and with a point resolution of less than 2 μm. SiD proposes a detector with five layers, and end caps, ILD proposes a detector with 3 long double layers, where within each double layer the two sides are separated by something like 1 mm. With an inner radius of 15 mm simulations have shown that the occupancy of the inner layer from background hits is at the level of a few percents. While this is still significant in the number of points and thus in the total data volume to be handled, it is not

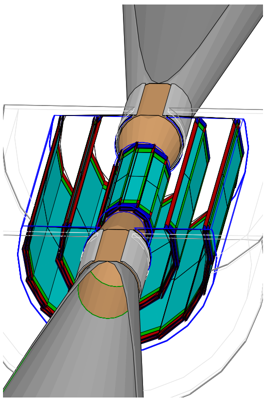

Figure 4: Layout of one version of a vertex detector. A total of six thin layers are arranged in three pairs so that each layer not only measures a highly precise space point, but also a direction.

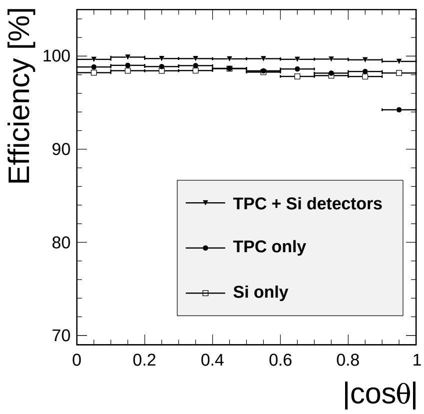

Figure 5: Tracking efficiency of the ILD concept as a function of $\cos\theta$. Also shown are the contributions of the individual tracking systems.

large enough to pose a significant threat to the efficiency of the innermost layer.

A number of different technologies are under consideration for the vertex detector. Even for the fairly long inter-bunch distances at the ILC readout of a complete pixel layer in between bunches is not possible. Depending on the technology hits from several bunch crossing will be accumulated before the detector can be readout. Some technologies (e.g. the ISIS proposal) propose to integrate intelligence into each pixel, to process and store several hits in the pixel, until the system can be read out. Others really on a fast readout, like the traditional CCD, or the MAPS technology, and use a high degree of sophistication in the readout to minimize the readout times. An extreme approach is followed by the fine pixel collaboration, which have decreased the pixel size by roughly a factor of 10 in area, and thus reduce at the ILC the occupancy for one complete train to a point that readout is only needed after a complete bunch train.

A major challenge for the developer is the reduction of material in the pixel detector. Technologies like CCD, MAPS, DEPFET etc all lend themselves to thinning of the sensors. Devices of 50 μm thickness are anticipated, and have been demonstrated in prototypes. Highly advanced support structures are needed to integrated these very thin and mechanically unstable devices into ladders which can be reliably operated in a collider environment. In fig 4 the layout of one version of such a vertex detector is shown.

Because of the long time between bunch trains, the systems is designed to not need any active cooling. Flowing the central detector with cooled gas should be sufficient to maintain the operating conditions throughout a bunch train.

Outside the vertex detector silicon strip detectors add additional precision points. For the ILD concept two layers are proposed to bridge the gap between the vertex detector and the time projection chamber. For the SiD detector, silicon strip detectors are used for the complete tracker system.

Silicon strip detectors are mature devices, which have been used in many detectors over the last years. A challenge for the ILC detector is to reduce the material in these devices, to design stable but light weight support structures, and to reduce the power consumption to a point that extensive active cooling is not needed. In the case of the ILD detector, the two layers of strip detectors are designed to provide two points with a point resolution of 10 μm with high efficiency. The two layers are placed one layer a few cm outside the last vertex detector, the second layer placed close the inner field cage of the time projection chamber. Both layers will most probably be suspended from the TPC, but will be mechanically decoupled through remote controlled movers that the silicon detector can be aligned relative to the vertex detector independently of the time projection chamber.

A challenge for this system is to maintain and reach excellent alignment. Several alignment systems are under discussion. Tracks from particles will play a central role, but additional systems based on laser beams will be needed to reach an initial alignment and to monitor the system.

The time projection chamber of the ILD concept is a large volume high precision chamber. It is split into two volumes in the center of the detector, which are then drifting to both sides of the experiments. Amplification of the primary charge is done in a system of micro pattern gas detectors, which cover the endplate. Several technological options are under consideration, using both gas electron multipliers (GEM) and Micro Mesh Chambers (Micromegas). In test beam experiments point resolutions equivalent to 100 μm over the complete 2.5 m long drift distance have already been achieved.

The proposed time projection chamber will deliver around 200 three dimensional space points along each track. Pattern recognition will be possible in such a device with excellent efficiency, and no bias concerning the direction or angle of the track. Long lived particles, kinks, and also back scattered particles will be found and reconstructed easily.

The current designs call for a very light weight structure of the field cage, which should not introduce more than 3% of a radiation length in front of the calorimeter. Recently a prototype of a 10% piece of the TPC has been built, and has demonstrated that this goal is in reach. Particular attention will need to be given to the readout system at the endplates. Two alternative designs are under investigation. In the first one pads typically of 1×5 mm^2 are used to collect the charge, and are connected individually to a readout electronics, which measures both the time of arrival, and the charge. Work is under way to miniaturize the foot print of this readout, so that the space per channel, including all services, fits into one pad. The second approach relies on significantly smaller pixel sizes. The readout plane is realized in silicon, and the electronics is integrated into each pixel. Such chips already exist for application where no timing information is needed [9], and are currently extended to also provide timing information [10]. In this approach the number of pixels is large enough that a digital time projection chamber can be attempted. The charge per pixel is not recorded any more, only the number and location of pixels hit are stored. From the density of the pixels hit the total charge in a hit in the TPC can be measured.

Over the next few years the performance of a TPC for a linear collider application will be tested and measured in a number of test beam experiments. Technologies are under development which will allow to fill large areas with very little dead space. By 2012 enough information should be available that both GEM and Micromegas readout technologies should have been proven, and that a decision - if needed - between the options should be possible.

The performance of the different options for a tracking system for both the ILD and the SiD concept have been simulated in some detail. In figure 5 the simulated tracking efficiency is shown, from a complete and realistic simulation of the ILD tracking system.

4.4. Calorimetric Detectors

The considerations on particle flow and total event reconstruction strongly favor a calorimeter which stresses spatial resolution over one that stresses energy resolution. The focus of the developments in this region therefore have been over the past few years on the development of a highly granular calorimeter, both for electromagnetic and for hadronic calorimetry.

The overall layout of the proposed calorimeter system is shown in Fig. 6

The CALICE collaboration [11] has formed in recent years with the goal of understanding and developing a working model for such a calorimeter.

4.4.1. The Electromagnetic Calorimeter

The ideal calorimeter would provide a three dimensional picture of the shower developing inside the detector. This ideal detector can be approximated by a sampling calorimeter with the typical size of a cell given approximately by the Molière radius in the material. If this is backed up by many samples longitudinally along the shower, a detailed reconstruction of individual showers becomes possible. The reconstruction of particles in dense jets is helped by the fact that the calorimeter is immersed in the strong central magnetic field of 4T. This field helps to separate charged and neutral particles before they enter

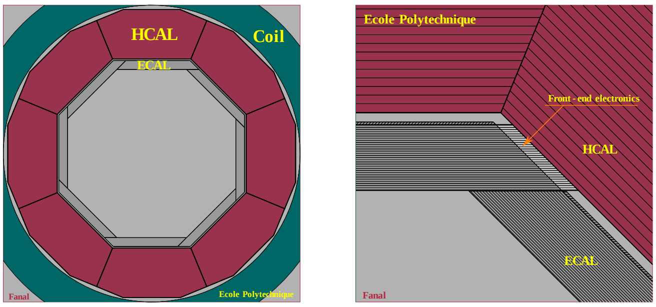

Figure 6: View of the barrel of the calorimeter, showing both the electromagnetic and the hadronic calorimeter. On the right the arrangement of the modules of the electromagnetic calorimeter are shown.

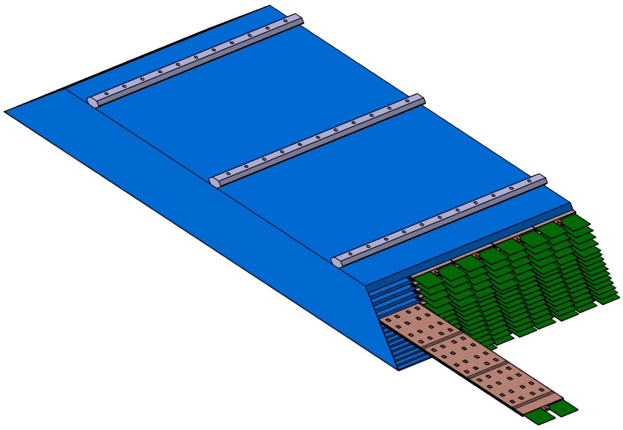

Figure 7: Drawing of one module of the proposed electromagnetic calorimeter. Active layers are inserted into the absorber structure as indicated by the one partially withdrawn module.

the calorimeter. An attractive solution to these requirements is a sampling calorimeter with the absorbers made from Tungsten, the active sensors from thin silicon diodes.

For a detector of the size and complexity as the ILC detector electromagnetic calorimeter presents a sizable challenge if it should be instrumented with Si diodes over its whole area. Many technological questions concerning reliability, production and cost of the sensors need to be answered before a final design can be attempted. However, preliminary investigations and simulations indicate that such a device would offer unchallenged performance and would significantly contribute to the physics potential of a linear collider. The design of one such module is shown in fig 7.

A more extreme ansatz is followed by the Spider group, which proposes to instrument the calorimeter with pixel detectors with pixel sizes of a few 10 μm [5]. This will give even more information on the shower structure, and promises to improve the shower reconstruction. It remains to be shown that such a calorimeter can be built at an affordable cost, and that the final performance of the detector is better than with the more conventional calorimeter discussed above.

4.4.2. *The Hadronic Calorimeter*

The hadronic calorimeter is lined up behind the electromagnetic modules, inside the coil. Together both measure the energy of neutral and charged particles. Two different solutions are currently under investigation.

The first approach is based on a conventional sampling calorimeter. The active medium is small scintillator tiles, read out via a system of wave-length shifting fibers and Silicon photo multipliers mounted directly on the tiles. The anticipated cell size is 3×3 cm^2 throughout the calorimeter, possibly slightly increasing towards the back end of the device. The reconstruction of particles in the calorimeter uses both the topological information from the position of hits and the energy information from the size of the deposit in the cell.

The second approach relies on a layout with very small cells also in the hadronic part. The only information extracted is whether a cell has been hit or not. No energy measurement per se is performed. Using topological information cells are combined into clusters, and the energy is reconstructed purely by counting the number of cells contributing to a cluster. The advantage of this approach is that it might allow an unprecedented tracking of particles inside a hadronic shower in the calorimeter, and thus help in separating overlapping charged and neutral particles. The drawback is the very large number of cells needed, which make new efficient and cheap detection and readout techniques necessary.

Both technologies undergo currently an intense program of prototyping and testing. The analogue version has been exposed to test beam at CERN and Fermilab, and results on the calibration, the linearity and the resolution are expected to be available very soon. The digital version will have a large scale test in 2010 in Fermilab. Data from both tests will then be used to validate the Monte Carlo models of hadronic showers, and to study parameters relevant for particle flow experimentally.

The resolution achieved with the prototype is illustrated in fig 8, before and after software weighting.

4.4.3. *Forward Calorimeter*

The physics at a linear collider calls for a hermetic calorimeter. The presence of intense beamstrahlung makes a dedicated approach to the very forward region necessary. The instrumentation in this region has to be able to survive the large background of mostly electromagnetic radiation emitted from the beam-beam interaction. At the same time it should be capable to at least veto large energy deposits by single particles.

In the current design two devices are foreseen, a Luminosity calorimeter (LumiCal), and a very forward calorimeter, used mostly to monitor the beam (BeamCal). Both are sampling calorimeters, built with large segmentation and fast readout systems to survive in the harsh environment. Particular emphasis needs to be placed on the radiation hardness of these devices, as they will need to operate in the presence of large electromagnetic backgrounds, and will need to stand very large neutron fluxes.

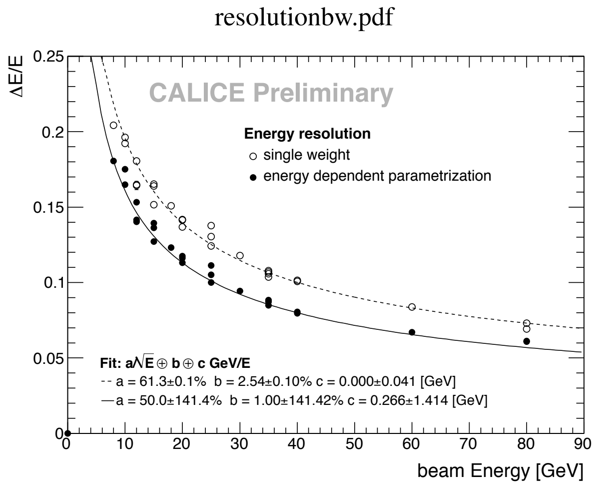

Figure 8: Resolution of the analogue HCAL measured in a pion test beam. Shown are the uncorrected resolution, and the resolution obtained after a software based weighting method, to compensate for the different response of the calorimeter to electrons and hadrons.

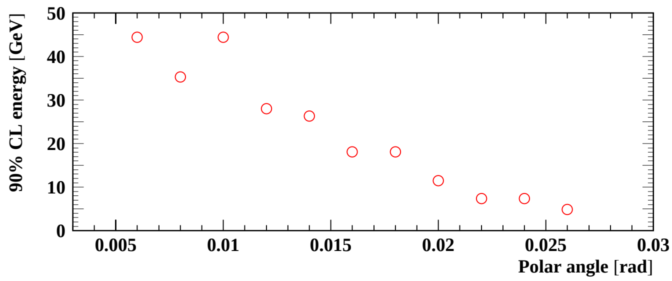

Figure 9: Detection capability of the low angle calorimeter: shown is the 90% CL energy vs. the polar angle. If an electron hits the calorimeter face with an energy larger than the one indicated it can be separated from the background with better than 90% probability.

In Fig. 9 the energy is shown, as a function of the polar angle, above which an electron hitting the calorimeter is still distinguishable from the background with 90% confidence. The plot shows that down to very small angles a reasonable vetoing capability is preserved.

5. Summary and Conclusion

Over the past few years groups have formed which propose integrated concepts for a detector at a linear collider. Two groups, ILD and SiD, have recently been validated by an international advisory group, and have been asked to proceed towards a complete design of the detectors.

Experimentation at a linear collider presents the experimenter with many challenges, both technical and conceptionally in terms of reconstruction. Progress has been made to identify suitable technologies. Particle flow as the method of choice for the event reconstruction has been established. Large experimental efforts are currently under way to demonstrate the feasibility of the particle flow approach not only in simulation, but also experimentally. Novel technological solutions are under investigation for most of the subdetectors.

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