Abstract

The 4th Concept detector presently being designed for the International Linear Collider introduces several innovations in order to achieve the necessary experimental goal of a detector that is 2-to-10 times better than the already excellent SLC and LEP detectors. We introduce a dual-readout calorimeter system, a cluster counting drift chamber, and a second solenoid to return the magnetic flux without iron. We discuss particle identification, momentum and energy resolutions, and the machine-detector interface that together offer the possibility of a very high-performance detector for $e^+e^-$ physics up to $\sqrt{s} = 1$ TeV.
1 Introduction

The physics reach of a new high energy $e^+e^-$ linear collider requires [1] the detection of all known partons of the standard model ($e, \mu, \tau, uds, c, b, W, Z, \gamma, \nu$) including the hadronic decays of the gauge bosons, $W \rightarrow q\bar{q}$ and $Z \rightarrow q\bar{q}$ and, by subtraction, the missing neutrinos in $W \rightarrow e\nu$, $W \rightarrow \mu\nu$, $\tau \rightarrow \ell\nu\nu$, and $\tau \rightarrow h\nu$ decays so that kinematically over-constrained final states can be achieved. The main benchmark process is

$$e^+e^- \rightarrow H^0Z^0 \rightarrow (\text{anything}) + \mu^+\mu^-$$

in which the two $\mu$s are measured in the tracking system and the Higgs is seen in the missing mass distribution against the $\mu^+\mu^-$ system. A momentum resolution of $\sigma_p/p^2 \approx 4 \times 10^{-5}$ (GeV/c)$^{-1}$ is required for a desired Higgs mass resolution of 150 MeV/c$^2$ in a 500 fb$^{-1}$ data sample. There are three main technologies under study to achieve this performance: a 5-layer silicon strip tracker, a TPC with sophisticated high-precision end planes, and a cluster-counting drift chamber [2].

This same final state can be studied for $Z \rightarrow q\bar{q}$ decays which are 20 times more plentiful than $Z \rightarrow \mu^+\mu^-$ decays but less distinct experimentally. In addition, those processes that produce $W$ and $Z$ bosons either by production ($e^+e^- \rightarrow W^+W^-, Z^0Z^0, HHZ$) or by decay ($H \rightarrow W^+W^-$), will reply critically on the direct mass resolution on $Z \rightarrow q\bar{q}$ and $W \rightarrow q\bar{q}$ decays, and these processes demand that the calorimeter energy resolution be $\sigma_E/E \approx 30%/\sqrt{E}$ with a constant term less than 1%. There are two main technologies under study: a highly segmented calorimeter volume with approximately (1 cm)$^3$ channels for the implementation of Particle Flow Analysis (PFA) algorithms, and dual-readout optical calorimeters that measure both scintillation and Cerenkov light [3].

The identification of $b$ and $c$ quark and $\tau$ lepton decays is critical to good physics since these massive particles are a gateway to the decays of more massive, and possibly new, particles [4]. The measurement of their respective decay lengths places stringent conditions on the spatial precision of a vertex chamber and how close it can be to the beam interaction spot. Typically, a spatial resolution of $\sigma \approx 5 \mu$m is desired, with large solid angular coverage. The inner radius is limited by the debris from beamstrahlung that is only suppressed by the axial tracking magnetic field; the uncharged debris cannot be suppressed.

The region beyond the calorimeter is reserved for, typically, a hadron absorber or muon filter to supplement the absorbing calorimeter. This absorber is always iron to provide mechanical support for the detector elements inside and to return the magnetic flux generated by a superconducting solenoid that establishes the uniform momentum tracking field. There are two main types of muon systems under study: an iron absorber interspersed with tracking chambers to measure the trajectories of penetrating tracks, and an iron-free design in which the magnetic flux is returned by a second outer solenoid.

2 The 4th Concept

We have introduced new ideas and instruments in order to achieve the resolution requirements needed for ILC physics studies [5]. With the exception of the vertex chamber, we have departed from the detectors at SLC and LEP and from the three ILC concept detectors GLD, LDC, and SID in all three major detector systems: the tracking, the calorimeter and the muon system. The 4th detector is displayed in Figure 1 showing the beam transport through the final focus, the dual solenoids (red), the crystal and fiber dual-readout

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calorimeters (yellow), the tracking chamber, and the vertex chamber. The muon tracking is in the annulus between the solenoids. A forward toroid for high precision forward tracking in under current study in this figure. Without iron, this detector is about 1/10 the mass of a conventional detector.

### 2.1 Tracking by cluster counting in a low-mass He-based drift chamber

The gaseous central tracker is under study as a cluster-counting drift chamber modelled on the successful KLOE main tracking chamber [2, 6]. This drift chamber (CluCou) maintains very low multiple scattering due to a He-based gas and aluminum wires in the tracking volume and utilizes carbon fiber end plates. Forward tracks (beyond \( \cos \theta \approx 0.7 \)) which penetrate the wire support frame and electronics pass through only about 15-20% \( X_0 \) of material. The low mass of the tracker directly improves momentum resolution in the multiple scattering dominated region below 10 GeV/c. The He gas has a low drift velocity which allows a new cluster counting technique that clocks in individual ionization clusters on every wire, providing an estimated 50 micron spatial resolution per point, a \( dE/dx \) resolution near 3%, \( z \)-coordinate information on each track segment through an effective dip angle measurement, and a layout made exclusively of super-layers with alternated opposite sign stereo angles. The maximum drift time in each cell is less than the 300 ns beam crossing interval, so this chamber sees only one crossing per readout. Data from a test of cluster counting are shown in Figure 2.

The critical issues of occupancy and two-track resolution are being simulated for ILC events and expected machine and event backgrounds, and direct GHz cluster counting experiments are being performed. This chamber has timing and pattern recognition capabilities midway between the faster, higher precision silicon tracker and the slower, full imaging TPC, and is superior to both with respect to its low multiple scattering.

The low-mass of the tracking medium, the multiplicity of point measurements, and the point spatial precision allow this chamber to reach \( \sigma_p/p^2 \approx 5 \times 10^{-5} (\text{GeV}/c)^{-1} \) at high momenta, and to maintain good momentum resolution down to low momenta.

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2.2 Calorimetry by dual-readout of scintillation and Čerenkov light

The calorimeter is a spatially fine-grained dual-readout fiber sampling calorimeter augmented with the ability to measure the neutron content of a shower. The dual fibers are sensitive to scintillation and Čerenkov radiation, for separation of the hadronic and electromagnetic components of hadronic showers \[7\], and since fluctuations in the EM fraction, i.e., fluctuations in \(\pi^0\) production, are largely responsible for poor hadronic energy resolution, the DREAM module achieved a substantial improvement in hadronic calorimetry. The energy resolution of the tested DREAM calorimeter should be surpassed with finer spatial sampling, neutron detection for the measurement of fluctuations in binding energy losses[8], and a larger volume test module to reduce leakage fluctuations. The calorimeter modules will have fibers up to their edges, and will be constructed for sub-millimeter close packing, with signal extraction at the outer radius so that the calorimeter system will approach full coverage without cracks. A dual-readout crystal in front of the deep fiber module consists of a crystal calorimeter with readout of both scintillation and Čerenkov light[1]. This provides better photoelectron statistics and therefore achieves better energy and spatial resolution for photons and electrons than is possible in the fiber calorimeter modules. The dual readout of these crystals is essential: over one-half of all hadrons interact in the so-called EM section, depositing widely fluctuating fractions of EM and hadronic energy losses.

The fiber calorimeter shows promise of excellent energy resolution on hadrons and jets, as seen in Figure 3 for 200 GeV \(\pi^-\): (a) the distribution of the scintillator (S) signal shows the raw resolution that a typical scintillating sampling calorimeter would achieve; (b) shows the leakage-dominated energy distribution using only the scintillating (S) and Čerenkov (C) signals for each event; and, (c) shows the energy distribution with leakage fluctuations suppressed using the known beam energy (=200 GeV) to make a better estimate of the EM fraction each event. The actual energy resolution of a fiber dual-readout calorimeter lies between Figures (b) and (c).

Finally, and very importantly, the hadronic response of this dual-readout calorimeter is demonstrated to be linear in hadronic energy from 20 to 300 GeV having been calibrated only with 40 GeV electrons, Fig. 4. This is a critical advantage at the ILC where calibration

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with 45 GeV electrons from $Z$ decay will suffice to maintain the energy scale up to 10 times this energy for physics.

2.3 Muon measurement without iron: a dual solenoid configuration

The muon system utilizes a dual-solenoid magnetic field configuration in which the flux from the inner solenoid is returned through the annulus between this inner solenoid and an outer solenoid oppositely driven with a smaller turn density \[10\]. The magnetic field in the volume between the two solenoids will back-bend muons which have penetrated the calorimeter and allow, with the addition of tracking chambers, a second momentum measurement. This will achieve high precision without the limitation of multiple scattering in $Fe$ that fundamentally limits momentum resolution in conventional muon systems to 10%. High spatial precision drift tubes with cluster counting electronics are used to measure tracks in this volume \[11\]. The dual-solenoid field is terminated by a novel “wall of coils” that provides muon bending down to small angles ($\cos \theta \approx 0.975$) and also allows good control of the magnetic environment on and near the beam line. The design is illustrated in Fig 5.

The path integral of the field in the annulus for a muon from the origin is about 3 T·m over $0 < \cos \theta < 0.85$ and remains larger than 0.5 T·m out to $\cos \theta = 0.975$, allowing both good momentum resolution and low-momentum acceptance over almost all of $4\pi$. \[11\]

For isolated tracks, the dual readout calorimeter independently provides a unique identification of muons relative to pions with a background track rejection of $10^4$, or better, through its separate measurements of ionization and radiative energy losses.

The detector’s magnetic field is confined essentially to a cylinder with negligible fringe fields, without the use of iron flux return. This scheme offers flexibility in controlling the fields along the beam axis. The twist compensation solenoid just outside the wall of coils is shown in the above figure, along with the beam line elements close to the IP. This iron-free configuration \[10\] allows us to mount all beam line elements on a single support and drastically reduce the effect of vibrations at the final focus (FF), essentially because the beams will coherently move up and down together. In addition, the FF elements can be brought close to the vertex chamber for better control of the beam crossing.

The open magnetic geometry of the 4th Concept also allows for future physics flexibility for asymmetric energy collisions, the installation of specialized detectors outside the inner solenoid, and magnetic flexibility for non-zero dispersion FF optics at the IP, adiabatic

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Figure 5: Drawings showing the two solenoids and the “wall of coils” that redirects the field out radially, and the resulting field lines in an $r - z$ view. This field is uniform to 1% at 3.5 T in the tracking region, and also uniform and smooth at $-1.5$ T in the muon tracking annulus between the solenoids.

Focusing at the IP, and monochromatization of the collisions to achieve a minimum energy spread \[10\]. Finally, this flexibility and openness does not prevent additions in later years to the detector or to the beam line, and therefore no physics is precluded by this detector concept.

3 Particle Identification

The capability to identify standard model partons ($e, \mu, \tau, u/d/s, c, b, t, W, Z, \gamma$) is equivalent to increased luminosity with larger and less ambiguous data ensembles available for physics analysis.

3.1 $\pi^0 \rightarrow \gamma \gamma$ separation and reconstruction

The dual-readout crystals can be made small, about 1cm$\times$1cm or 2cm$\times$2cm, and with reconstruction using shower shapes in the crystals we estimate that $\pi^0 \rightarrow \gamma \gamma$ can be reconstructed up to about $E_{\pi^0} \sim 20$ GeV, which is high enough to reconstruct the important decay $\tau \rightarrow \rho \nu \rightarrow \pi^\pm \pi^0 \nu \rightarrow \pi^\pm \gamma \gamma \nu$ to be used as a spin analyzer in the decays of higgs, etc.

3.2 $e, \pi, K, p$ separation by $dE/dx$ at lower momenta

The cluster counting central tracking chamber has the added benefit of an excellent energy loss measurement without a Landau tail since clusters are counted as opposed to energy losses summed. We anticipate 3% or better resolution in $dE/dx$ as an analysis tool in, for example, $b$ physics where a large fraction of charged tracks are below a few GeV/c.

3.3 $\mu$ separation from $\pi^\pm$

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In the 4th concept, we achieve excellent $\mu - \pi^\pm$ separation in the dual readout calorimeter and additional separation using energy balance from the tracker through the calorimeter into the muon spectrometer. A non-radiating $\mu$ has a zero Čerenkov signal in the fiber calorimeter since the Čerenkov angle is larger than the capture cone angle of the fiber. The scintillating fibers measure $dE/dx$ of the throughgoing $\mu$ [13]. Any radiation by the $\mu$ within the body of the calorimeter is sampled equally by the scintillating ($S$) and Čerenkov ($C$) fibers [12], and therefore $S - C \approx dE/dx$ independent of the amount of radiation. The distributions of $(S - C)$ vs. $(S + C)/2$ for 20 GeV and 200 GeV $\pi^-$ and $\mu^-$ are shown in Fig. 6 in which it is evident that for an isolated track the $\pi^\pm$ rejection against $\mu$ is about $10^4$ at 20 GeV and $10^5$ at 200 GeV. A further factor of 50 is obtained from the iron-free dual solenoid in which the precisely measured $\mu$ momentum can be matched with the momentum in the central tracker and the radiated energy in the calorimeter. Of course, we expect that other effects, such as tracking inefficiencies, will limit this level of rejection before these beam-measured rejections are achieved in practice.

### 3.4 $e$ separation from $\pi^\pm$ and jets ($j$)

The scintillation vs. the Čerenkov response of 40 GeV $e$ and 50 GeV $\pi^\pm$ is displayed in Fig. 7 in the DREAM test module [7, 12], showing the equal responses for $e$ and the $f_{\mu}$ fluctuations for $\pi^\pm$, and the obvious substantial rejection of $\pi^\pm$ against $e$. Just as the overall shower $C$ vs. $S$ response fluctuates, so do the individual channels of the $\pi^\pm$ generated showers. The statistic

$$\sigma_{Q-S} = \frac{1}{N} \sum_{i=1}^{N} (Q_i - S_i)^2$$

is a measure of these channel-to-channel fluctuations. For 100 GeV $e$ this $\sigma_e \approx 0.2$ GeV$^2$, and for $\pi^\pm$ $\sigma_{\pi} \approx 10$ GeV$^2$, yielding a rejection of $\pi^\pm$ against $e$ of about 50.

The time history of the scintillating signal contains independent information, in particular, the neutrons generated in the $\pi^\pm$ cascade travel slower ($v \sim 0.05c$) and fill a larger volume, and therefore the elapsed time of the scintillating signal is longer for a $\pi^\pm$ and an $e$. One statistic is the “full width at one-fifth maximum” shown in Fig. 7(b) for 80 GeV $e$ and $\pi^\pm$ in the SPCAL calorimeter [14]. These statistics will work just as well for $j$ separation from $e$ when the jet has a single forward high energy $\pi^\pm$.
The exploitation of these measurements in a collider experiment will depend on many factors, such as channel size, the character of event ensembles, and the fidelity of the measurements themselves. The goal of the 4th Concept is to package these capabilities into a comprehensive detector.

3.5 Time-of-flight with the dual-readout crystal and fiber calorimeters

The time history readout of the scintillating fibers will serve several purposes, \textit{viz.}, $e^{-} \pi^{-}$ separation (Fig. 7(b)), neutron measurement for the suppression of fluctuations in binding energy losses, and as a real-time nanosecond monitor of all activity in the volume between the 337-ns bunch crossings, including ‘flyers’ and beam burps of any kind.

In addition, the ns and even sub-ns resolution on the time of arrival of a shower can be used in the time-of-flight of heavy objects such as supersymmetric or technicolor particles that move slowly ($v \sim 0.1c$) into the tracking volume and decay to light particles ($e, \mu, \tau, j$, etc.). Such objects can be easily reconstructed in 4th.

4 Summary

The 4th Concept detector contains many new ideas in high energy physics instrumentation that are aimed at a comprehensive detector for 1 TeV $e^+e^-$ physics at the International Linear Collider. All of the data shown in this paper and all of the performance specifications have already been tested in either beam tests, prototypes, or existing detectors. The difficult problems of incorporating these small successful instruments into a large detector while maintaining the scientific strengths of each are good work in the near future.
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