R&D FOR FUTURE DETECTORS[*]

JAMES E. BRAU

Physics Department and Center for High Energy Physics, University of Oregon
Eugene, Oregon, 97403-1274, USA

Research and development of detector technology are critical to the future particle physics program. The goals of the International Linear Collider, in particular, require advances that are challenging, despite the progress driven in recent years by the needs of the Large Hadron Collider. The ILC detector goals and challenges are described and the program to address them is summarized.

1. Introduction

Detector R&D is advancing on many fronts of experimental particle physics, including efforts to produce massive, highly efficient, cost-effective detectors for future neutrino experiments, for experiments requiring high bandwidth and high precision, such as hadron B factories, rare kaon decay experiments, and tau/charm factories, and for linear collider experiments. In recent years, the needs of the Large Hadron Collider (LHC) experiments have driven many significant advances. Despite this, further developments are required. This paper surveys the current activities in detector R&D directed toward linear collider experiments.

1.1. *Linear Collider Detector Requirements*

The detector requirements for the linear collider experiments are dictated both by physics goals[1], as well as accelerator constraints. The physics goals impose the following demands:

1. Triggerless event collection with software event selection;
2. Extremely precise vertexing;
3. Synergistic design of detector components, combining vertex detection, tracking, and calorimetry in optimal jet reconstruction;
4. Precise momentum reconstruction; and

5. Nearly complete solid angle coverage and hermiticity.

These requirements present challenges that go beyond those addressed by LHC detector development. For example, the calorimeter goals include a "tracking" calorimeter, in which individual particle contributions are separately measured. This capability requires unprecedented granularity. Also, very thin pixel vertex detectors are required, again well beyond the capability of LHC detectors. These goals can only be achieved through effective detector R&D over the next few years. A coordinated, world-wide program is now being pursued[2].

The superconducting RF technology has recently been selected for the main accelerating structure of the International Linear Collider (ILC). With this decision, the accelerator constraints on detector design are now generally known. Table 1 presents some of the relevant parameters from the TESLA TDR design[3]; the ILC parameters will be similar to these, with some deviations.

2. Calorimetry

The events at the ILC are simple relative to those seen at a hadron collider, as illustrated in


Figure 1[4]. This being so, particle level reconstruction of jets is feasible, as opposed to the usual integrated jet reconstruction. (This approach is often referred to as particle flow, or energy flow, calorimetry.) Physics objectives again set the goals, and Figure 2 illustrates one

Table 1. Some key accelerator parameters for detector design (from the TESLA TDR for E_{CM} = 500 GeV[3]).

Bunches/train	2820
Trains/second	5
Bunch spacing	337 nsec
Bunches/second	14100
Length of train	950 μsec
Train spacing	199 msec
Crossing angle	0-35 mrad

calculation comparing the confusion between heavy boson pairs in $e^+e^- \rightarrow WW\nu\nu$ and $e^+e^- \rightarrow ZZ\nu\nu$ final states, for a jet energy resolution of 60%/√E or 30%/√E. This is one of the primary physics channels which sets the goal of 30%/√E for the jet resolution.

Figure 1. Simulation of linear collider produced t-tbar event at √s = 350 GeV[4].
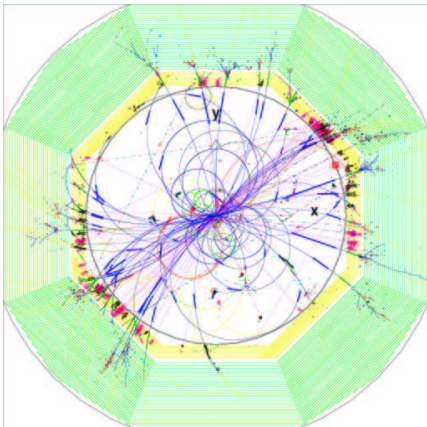
Since particle level reconstruction with good efficiency is conceivable at the ILC, the measurement of each individual element of a jet must be optimized, and each will play a

different role in the reconstruction. Charged particles carry the bulk of the jet energy (see Figure 3[5]), but the superiority of the tracking momentum resolution means it inherently plays a negligible role in the precision, assuming efficient reconstruction. This is illustrated in Table 2, which shows each of the components[6]. Perfect isolation of electromagnetic and hadronic energy depositions suggest particle level reconstruction could yield ~20%/√E or better. However, overlap of these elements results in confusion that degrades the reconstruction. The goal of 30%/√E is conceivable, but depends on careful design and optimization.

Figure 2. Simulation of di-jet mass distributions (m_{34} vs. m_{12}) in four-jet events. Left figure shows confusion resulting from jet energy resolution of 60%/√E, and right figure illustrates the separation resulting from 30%/√E.

$$e^+e^- \rightarrow WW\nu\bar{\nu} \quad , \quad e^+e^- \rightarrow ZZ\nu\bar{\nu}$$
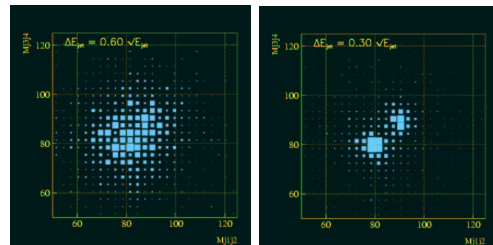

Figure 3. Visible jet energy fractions (in percent)[5]. The smaller component represents neutral hadrons. The larger fraction is charged particles. The third component is photons.
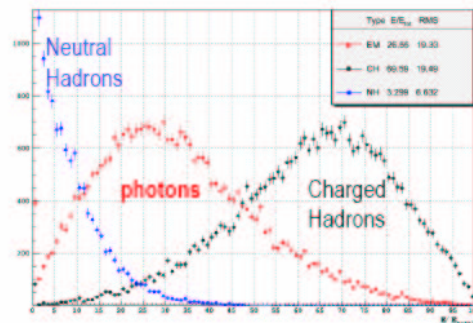
Table 2. Summary of feasible detector resolution goals for jet components[6].

Particles	Visible Energy Fraction	Detector	Resolution
Charged	~65%	Tracker	negligible
Photons	~25%	EM cal	~15%/√E
Neutral hadrons	~10%	EM cal +Had cal	~60%/√E
combined	**100%**		**~20%/√E**

2.1. *Electromagnetic Calorimetry*

Physics signals with isolated electrons and gammas require electromagnetic energy measurements of $< 15\% / \sqrt{E} \oplus 1\%$. The particle flow jet reconstruction requires a fine grained EM calorimeter to separate neutral EM clusters from charged tracks entering the calorimeter. The effectiveness of the fine granularity is limited by the effective Moliere radius, demanding a minimal value. Tungsten offers the smallest feasible value. The Moliere radius is increased by the sampling gaps, which demands the smallest practical gaps. Reconstruction of the photon showers is improved by separation of charged tracks from a jet core, which motivates maximizing BR^2, where B is the strength of the solenoidal magnetic field, and R is the radius of the EM calorimeter from the beamline.

A natural technology choice given these constraints is a silicon-tungsten (SiW) sampling calorimeter[7]. Good success was achieved using SiW for luminosity monitors at SLD[8], OPAL[9], and ALEPH[10]. Two groups are now developing SiW electromagnetic sampling calorimetry for the linear collider experiments. These are an Oregon/ SLAC/BNL collaboration, and the CALICE Collaboration.

The Oregon/SLAC/BNL group[11] is developing a conceptual design for a dense, fine grained SiW calorimeter, envisioning a transverse segmentation of the hexagonal silicon cells of about 5 mm, well matched to the Moliere radius of tungsten, which is preserved with 1 mm sampling gaps for 3.5-4 mm tungsten radiator thicknesses. Each sensor, fabricated from a six inch silicon wafer, is read out by one frontend chip mounted directly on the sensor, and 30 longitudinal samples gives an EM resolution of ~15%/√E. First silicon detector prototypes have been procured, and testing and electronics design is well underway. A dynamically switchable feedback capacitor scheme is planned to achieve a dynamic range of 0.1-2500 mips. Electronics will be bump bonded to the detectors, with test beam studies beginning in 2005. It may be possible to passively cool the calorimeter with conduction of heat out through the tungsten radiator.

CALICE [12] is building a SiW physics prototype calorimeter of 9720 channels in a volume of 20cm x 32 cm x 32 cm. The square silicon pads are 1 cm^2. The calorimeter is planned to be tested in a DESY beam in late 2004. During 2005, this electromagnetic calorimeter will be tested along with CALICE hadronic calorimeter prototypes in a hadron beam.

A number of other concepts are being developed for the electromagnetic calorimeter, including scintillator tile-fiber with a number of possible modern readouts and shower-max sampling with silicon or strips, silicon-scintillator hybrid, shashlik, and scintillator strip.
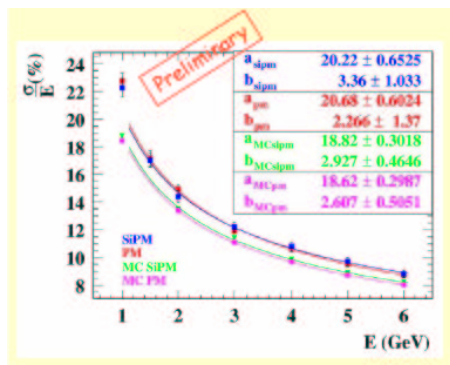
2.2. *Hadronic Calorimetry*

The primary role of the hadron calorimeter in particle flow is to isolate and measure the energy of neutral hadrons. As Table 2 shows, this is one of the major limitations on the ultimate jet energy resolution. Several technologies are being developed for this role and for hadron calorimetry in general: resistive plate chambers (RPCs), gas electron multipliers (GEMs), sintillator strips, and scintillating tile-

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fibers read out with avalanche photodiodes (APDs), silicon photomultipliers (SiPMs), hybrid photodiodes (HPDs), or electron bombarded charged coupled devices (EBCCDs). The readout may be either analog, or digital.

The MINICAL calorimeter prototype module has been built and tested by Hamburg, DESY, Dubna, MEPhI, Prague, LPI, and ITEP[13]. The calorimeter is based on 2 cm steel radiator layers, with 5 mm gaps for the plastic scintillator tile sampling. The readout systems studied include PMs, SiPMs, and APDs. A reliable calibration system was established, long term stability was checked, and a detailed Monte Carlo simulation was compared. Results of these tests with electrons are shown in Figure 4, where the energy resolution as a function of energy for the tested SiPM and PM readouts are compared to Monte Carlo simulations. Tests with hadrons are planned in 2005.

Figure 4. MINICAL resolution results with electrons compared to Monte Carlo simulation[13].

A group involving Argonne, BU, Chicago, Fermilab, and UT Arlington has designed a $1m^3$ calorimeter, including a test of digital hadronic calorimetry[14]. The structure will allow both RPC and GEM readout configurations. The objectives of this program include validation of the RPC approach (technique and physics), validation of the concept of the electronic readout, measurement of hadronic showers with unprecedented resolution which leads to validation of Monte Carlo simulations of hadronic showers, and comparison of digital calorimeter results with analog calorimetry.

Compensating calorimetry has also been investigated with extensive beam tests[15], and preshower and shower max detector have been tested[16].

3. Tracking

Tracking for any modern experiment should be conceived as an integrated system. Following this philosophy, the linear collider detectors aim for a combined, integrated optimization of: The inner tracking (vertex detection); The central tracking; The forward tracking; And a highly granular electromagnetic calorimeter. Pixelated vertex detectors are capable of track reconstruction on their own, as was demonstrated by the 307 Mpixel CCD vertex detector of SLD[17] with three barrel coverage. An advanced, pixelated, multi-layer vertex detector is being planned for the linear collider. Track reconstruction in the vertex detector impacts the role of the central and forward tracking system. Detection of the Higgs boson in the recoil mass distribution against the Z sets a resolution goal of $\sim 5 \times 10^{-5}$.

3.1. Inner Tracking – Vertex Detection

The linear collider vertex detector requirements include excellent spacepoint precision (<4 microns), superb impact parameter resolution ($\sim 5\mu m \oplus 10\mu m/(p \sin^{3/2}\theta)$), transparency ($\sim 0.1\%$ X0 per layer), and excellent pattern recognition capability, with tracks found in the vertex detector on its own. Four or five layers of pixelated detectors are conceived for the linear collider vertex detector to ensure highly efficient standalone tracking.

Concepts now under development for the linear collider include Charge-Coupled Devices (CCDs), which have a significant advantage of having been demonstrated in a large system at SLD, Monolithic Active Pixels (CMOS or MAPs), the DEpleted P-channel Field Effect Transistor (DEPFET), Silicon on Insulator (SoI), Image Sensor with In-Situ Storage (ISIS), and HAPS (Hybrid Pixel Sensors).

The key issues for CCDs are readout speed and timing, material budget, power consumption, and radiation hardness. Some of the properties achieved with the SLD vertex detector are illustrated in Table 3.

Table 3. Some key parameters of the SLD vertex detector[17]. The space point resolution is averaged over all 307 Mpixels, for the two years of operation.

Pixels	3.07×10^8
Readout speed	5 MHz $\otimes$ 96 channels
Transparency	0.4%/layer
Power	~15 Watts @ 190K
Space point resolution	3.9 μm

The Linear Collider Flavour Identification Collaboration (LCFI; Bristol, Glasgow, Lancaster, Liverpool, Oxford, and RAL) has developed a column parallel readout CCD to significantly reduce the time needed to read out signals from the detector. The ILC bunch train length of ~1 msec is too short for multiple image readout with conventional CCDs, and integration over the train results in unacceptably large backgrounds in the inner layers. The column parallel readout scheme allows each column of the CCD to be read out in parallel, rather than all columns passing serially through the readout register, as in the common CCD readout concept, thus reducing the readout time to a fraction of the bunch train. This requires a separate amplifier for each column. The LCFI Collaboration has achieved a small working prototype CCD, operating with column parallel readout, and observed 100 electrons noise, clocking with 1.9 volts. The maximum readout speed was 25MHz, and future developments are planned.[18]

The interference of electromagnetic pulses generated by the passing beam bunches in the inner detector are a serious concern; SLD observed a significant interference, but was able to overcome the problem by delaying the readout for 100 μsec. This is not an option for the ILC, with bunch spacings of about 300 nsec. If such interference is unavoidable at the ILC, it might be possible and necessary to store charge deep within the detector until the ambient environment is acceptable, which is the motivation for development of the ISIS.[18] This technique has been pioneered in industry[19] for other reasons. For the ILC, 20 storage registers per cell are envisioned, allowing the long bunch train to be subdivided during its passage, without readout. Time slicing is achieved by shifting deep storage registers every 50 μsec. This is expected to create a totally noise-free charge storage, ready for readout during the 199 msec of calm conditions between bunch trains.

CCDs are sensitive to radiation damage, particularly since they require the transferring of charge over long distances within the silicon. The anticipated exposure at the ILC is ~5×10^{11}/cm^2/yr of ~20 MeV electrons at layer-one and ~10^9/cm^2/yr 1 MeV-equivalent neutron dose from the extracted beamline. Neutrons will create harmful clusters. Low energy electrons create only point defects, but high energy electrons have also been shown to create cluster damage.[20] The number of effective damage clusters depends on the occupation time, and some will have very long time constants.[21]

In a series of studies of the impact of neutron and electron radiation on SLD CCDs, a technique was developed to measure trapping effects at the pixel level, as illustrated in Figure 5. It has been found[22] that annealing is not observed over a five year period when the CCDs were stored at room temperature, trapping times can extend to milliseconds (in contrast to the expected nanosecond time scale), and the charge trap clusters produced by high energy electron beams are smaller, but more numerous than those produced in neutron damage. The traps can be quenched temporarily with a dummy signal charge, suggesting a possible mechanism for hardening.

Figure 5. Image of the CCD, showing pixel traps[22].
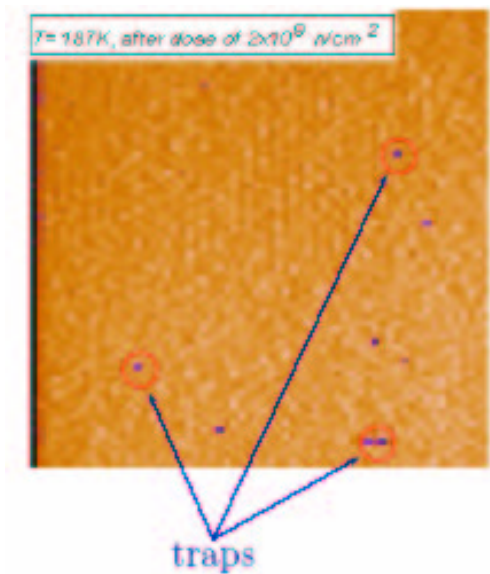
Other important efforts on vertex detection for the ILC include monolithic active pixel detectors based on CMOS technology, and the DEPFET devices. The CMOS detectors are based on standard VLSI chips, with a thin, un-doped silicon sensitive layer, operated undepleted. The advantages include decoupling the charge sensing and signal transfer functions (which improves radiation tolerance and permits random access), the small pitch which is possible (yielding the desired high tracking precision of pixel detectors), and their potential for thin structures, fast readout, and moderate price. Two groups have produced such detectors, with the ILC in mind. The Strasbourg IReS group has been working on the development of monolithic active pixels since 1989[23]. The first IReS prototype arrays of a few thousands of pixels demonstrated the viability of the technology and its high tracking performances. The first large prototypes have now been fabricated and are being tested. Current attention is focused on readout strategies adapted to the specific experimental conditions. The second detectors have been developed by an RAL group.[24] These, known as Flexible Active Pixels (FAPs) include the integration of 10-20 storage registers per pixel.

The DEPFET (DEPleted Field Effect Transistor)[25] detectors employ a field effect transistor on top of fully depleted bulk. All charge generated by a passing charged particle assembles underneath the transistor channel and modifies the transistor current. Reset is achieved by a positive pulse on the clear electrode. In this way, the sensor and amplifier functions are combined into a single device. Advocates note advantages which include the low capacitances (low noise), undisturbed signal charge with readout, noise-free reset of signal charge, large signal for a mip, low power consumption, and operation over very large temperature range.

3.2. Central Tracking

In general, two approaches to central tracking are being developed for the ILC: gaseous tracking based on a Time Projection Chamber (TPC) or a jet drift chamber, and silicon tracking. The TPC approach builds on the successful experience of PEP-4, TOPAZ,

ALEPH, ALICE, DELPHI, STAR, etc. with a large number of space points, making reconstruction straight-forward. The dE/dx capability which provides particle ID is a bonus. The minimal material in the barrel is valuable for calorimetry. Tracking extends out to large radii. Silicon tracking, on the other hand, provides superb spacepoint precision, which allows the tracking measurement goals to be achieved in a compact tracking volume. It is also robust to spurious, intermittent backgrounds, such as those experienced at the much lower luminosity SLC, and anticipated by many at the ILC. The operation of a linear collider differs from a storage ring, being susceptible to independent instabilities from bunch crossing to bunch crossing.

TPC Tracking

There are a number of issues for the ILC TPC application. First there is the optimization of the novel gas amplification systems. While conventional TPC readout has been based on MWPCs and pads, this approach is limited by positive ion feedback and MWPC response. This conventional approach is being improved by replacing the MWPC readout with micropattern gas detectors (MPGDs), such as gas electron multipliers (GEMs)[26] and Micromegas[27]. Among the improvements are the absence of E×B effects since these are small structures, the inherent 2D geometry, sensitivity to only the fast electron signal, and the intrinsic ion feedback suppression. The other issues under attack are the neutron backgrounds, optimization of single point and double track resolution, performance in high magnetic fields, and demonstration of large system performance with control of the systematic errors, including performance in a magnetic field. A final issue is minimization of the total material necessary for the inner and outer field cage and the end plate.

Figure 6 presents the results for transverse point resolution in a GEM equipped TPC vs. drift

time for various magnetic field strengths. The resolution improves up to about 1 Tesla[28].

Figure 6. Transverse resolution measured in a GEM equipped TPC with Ar/CH$_4$ (95/5) vs. drift time for B=0, B=0.9 Tesla, and B=1.5 Tesla.[28]
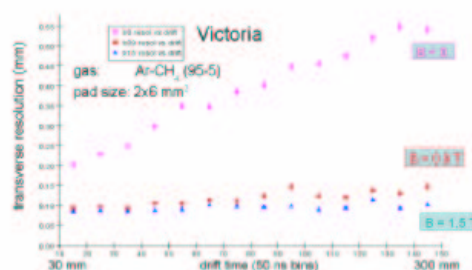

Figure 7. Ion feedback versus magnetic field for GEMs(upper) and Micromegas(lower)[29].
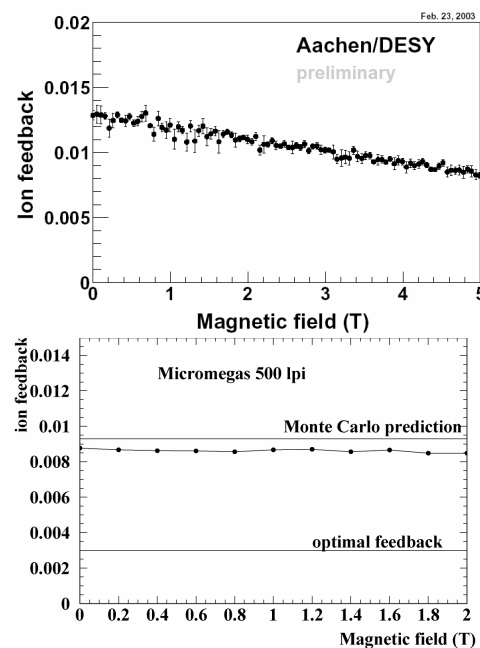

Figure 7 shows the effect of magnetic field on ion feedback in a GEM equipped TPC (upper figure) and a Micromegas equipped TPC (lower figure)[29]. The ion feedback is seen to

decrease with magnetic field in the GEM system, likely due to enhanced electron extraction efficiency. The ion feedback in the micromegas system does not depend on field, as is expected.

Recently, MPGD based TPC R&D has begun in Asia, in collaboration with the European efforts.

Silicon Tracking

While the TPC tracker requires 100-200 bunch crossings to be fully read out, a silicon tracker has a live time that can be limited to one crossing. ILC backgrounds (especially those associated with beam loss, extrapolated from SLC experience) could make this a critical factor, and are a significant motivation for the silicon tracking detector, SiD[30]. Furthermore, with superb position resolution, even a compact silicon tracker can achieve the linear collider tracking resolution goals. The compact tracker then allows for a smaller and cheaper calorimeter, allowing more aggressive technical choices to be pursued within the same cost umbrella. The silicon tracking layer thickness determines the low momentum performance. Figure 8 illustrates the expected momentum resolution, and compares it to a TPC tracker labeled L[31]. A measurement of the third, longitudinal dimension may be achieved with segmented microstrips or silicon drift detectors.

Alternative silicon tracking configuration are possible, of course, and two such configurations, differing in the amount of supporting and readout material, are illustrated in Figure 9[32].

Strip length is a variable, and optimization of performance will determine the choice. Short strip segments (10 cm slices, for example) are interesting for their lower noise level, shorter shaping time, and better time stamping. Longer strips with long shaping time are also of interest, and under development[33], motivated by minimized material in the tracking volume.

Two ASICs for long shaping will soon go to fabrication. [34]

Figure 8. Momentum resolution versus momentum for normal incidence, 90 degrees to the beamline[31].
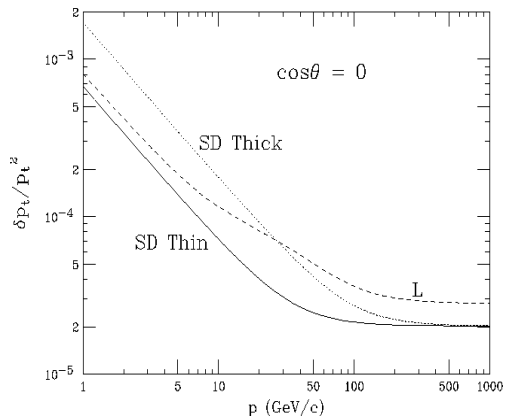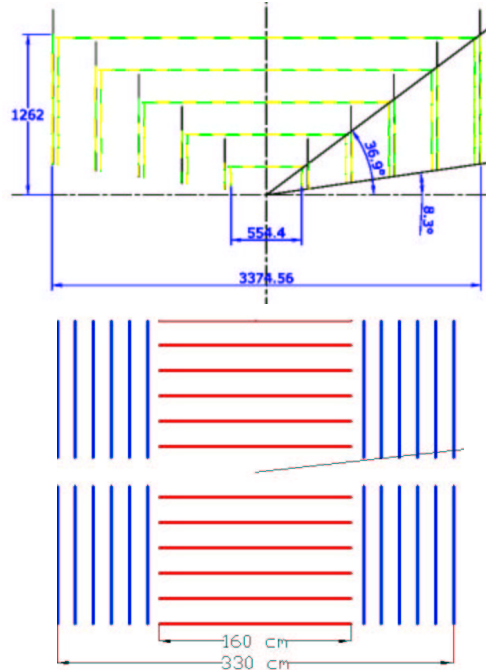

Figure 9. Two alternate topologies being investigated for the silicon tracker design[32].

Highly efficient reconstruction of all tracks, including those from the neutral strange particles which decay in the tracking volume, is required. Studies of this capability are underway.[35]

4. Very Forward Instrumentation

Hermiticity depends on excellent coverage in the forward region. The forward system plays several roles, including maximizing the detector hermiticity, measuring the luminosity with precision, shielding the tracking volume, and monitoring beamstrahlung. It must operate in a very high radiation environment, with 10 MGy/ year anticipated in the very forward detectors.

Optimization of the forward detectors must be closely coordinated with the constraints of the collider. Therefore, this effort becomes an element of the machine-detector interface(MDI) effort. MDI is a critical area of the detector, and R&D must be directed at its optimization. Goals include preserving an optimal hermeticity preserving good measurements, controlling backgrounds, and stabilizing the final quads of the collider. Figure 10a shows the configuration developed for the TESLA collider with no crossing angle[36], and Figure 10b shows the ILC configuration for the 20 mrad crossing angle option[37].

5. Beamline Instrumentation

Beamline instrumentation is required to fulfill the physics goals of the ILC. Here, again, detailed interaction between the detector design and the collider is critical. The capabilities required of the beamline instrumentation include measurements of 1.) the beam polarization (electrons and possibly positrons), 2.) luminosity weighted center of mass energy of the interacting particles, and 3.) differential luminosity. The polarization should be measured with 0.2% precision, the energy with

200 ppm, and the differential luminosity measurement requires knowledge of beamstrahlung effects. Vigorous R&D in this area is underway.[38]

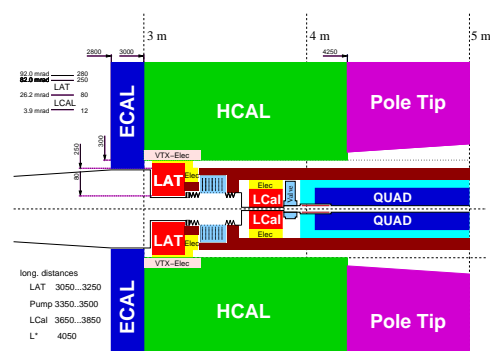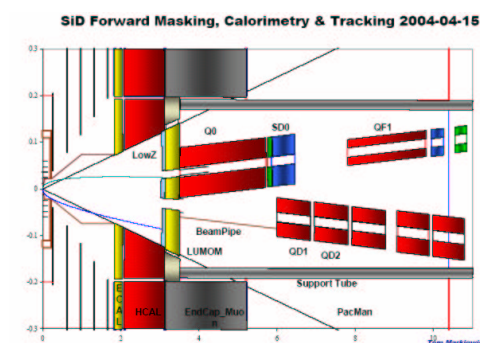Figure 10a. Zero crossing angle forward calorimetry system developed for TESLA[36].

Figure 10b. 20 degree crossing angle system developed for the Silicon Detector (SiD)[37].

6. Other Detector R&D

Completing the detectors requires R&D on a number of additional components, including muon detectors and solenoidal magnets.

For muon detection, resistive plate chambers are an attractive approach, and an interesting new construction technique has been presented[39]. Another alternative being actively investigated for the muon detectors is that of scintillator

strips with multianode photomultiplier tubes (MAPMTs).

All detector concepts under study assume a strong magnetic field of strength between 3 and 5 Tesla, with a coil of large diameter. The large volume required for this high-field magnet is a challenge, but experience with the 4 Tesla CMS solenoid will be very helpful. This experience has been utilized in present detector designs, but requires additional understanding. It is also important to study field compensation issues if the collider employs a crossing angle in the interaction region.

7. Summary

The linear collider experimental program needs advances in detector technology specific to the challenges of the ILC: High granularity, high precision, high efficiency, triggerless operation. A coordinated R&D effort is underway world-wide to develop the advanced detectors needed to capitalize on the special discovery opportunities which will be created by the construction of the International Linear Collider.

Acknowledgments

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