REVIEW OF DETECTOR CONCEPTS *

DEAN KARLEN[1 #]

[1] *Department of Physics and Astronomy, University of Victoria, Canada*

Abstract

This paper presents a brief overview of detector concepts under consideration by the Asian, European, and North American communities for a future linear collider experiment.

1 Introduction

The future linear collider requires a detector that is novel in many respects, in order to achieve the stated performance goals, which far exceed the capabilities of existing detectors. In particular, the detector requires a very low mass, yet precise, pixel vertex tracker, excellent momentum resolution over a wide range of energies, and superb jet energy resolution.

Last year, concepts for detectors to meet these objectives were published by the Asian[1], European[2], and North American[3] communities. More recently, representatives from all three regions have prepared a paper that outlines the global efforts in detector research and development aimed at bringing these concepts to reality.[4]

This paper presents a brief overview of the current ideas for the detector components. For each subsystem, there are several options, and therefore important choices will need to be made. In order to be able to make the right decisions further input is required, in the areas of detector simulations, hardware research and development, and physicist insight.

* This work is supported in part by Natural Sciences and Engineering Research Council of Canada
# e-mail address: karlen@uvic.ca

Investment of effort in these areas is growing and will allow our community to build the best detector possible in the future.

2 Vertex Detector

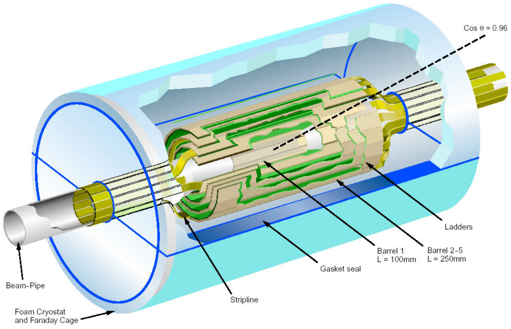

Figure 1 General layout of a CCD-based vertex detector.[2]

In general terms, the vertex detector is required to measure a few very precise points on tracks very close to the interaction point. This allows the linear collider detector to have very good *b*-tagging capability, especially important to efficiently identify multiple *b* final states that may arise from $e^+e^- \rightarrow ZZH$ or $t\bar{t}H$, and good *c*-tagging capability, which is important for separating $H \rightarrow c\bar{c}$ from $H \rightarrow b\bar{b}$ events. It also allows tracks to be correctly assigned to secondary and tertiary vertices, in order to calculate the vertex charge. Finally, the precise points from the vertex detector improve the overall momentum resolution of the linear collider detector.

There is general consensus that the optimum vertex detector design to achieve these goals consists of pixel devices arranged in cylindrical layers, as shown in Figure 1. The power such a design was clearly demonstrated by the SLD experiment. Small pixel sizes are important to avoid confusion from multiple tracks in jets and from background. In order to be able to do stand alone tracking, 4 or 5 layers are envisaged, which will allow internal alignment and track efficiency measurements. The first layer needs to be as close as possible to the interaction point, but because of the high occupancy, it would be matched last in tracking algorithms.

Cylindrical designs lead to large material thickness in the forward directions, which may be especially important for studying certain *t*-channel processes at high energies. Because of this and the requirements for good *c*-tagging for all angles, the goal for layer thickness has been set at 0.1 – 0.2% X_0 or less, significantly less than the SLD layer thickness of 0.4% X_0. Possible solutions under consideration include the use thin devices supported directly by tension or by gluing to a thin substrate under tension.[5]

Expected machine background levels appear to be tolerable. The 4 Tesla magnetic field reduces the large pair background entering the detector, allowing the first layer to be at a radius of 1.25 cm, while maintaining an occupancy rate of about 0.1% or less for an integration time of 100 beam crossings. The expected ionizing radiation dose of 100 krad in 5 years and neutron flux of 10^9/cm^2/yr are within current CCD tolerances, and other detector technologies are expected to be more radiation resistant.

The CCD conceptual design calls for 800 million 20 × 20 μm^2 pixels, yielding a point resolution of 2-5 μm. For comparison, the SLD detector had 300 million pixels and achieved a resolution of 4 μm. In order to increase the readout speed to 50 MHz, necessary for the TESLA beam structure, column parallel readout designs are being developed. The fast readout may have the additional advantage of removing the need for a cryostat, used to reduce dark current.[5]

CMOS monolithic active pixel sensors (MAPS) offer the same pixel size and precision as CCDs.[6] For these devices, the charge is sensed at each pixel, which may lead to high power consumption and therefore require pulsed powering. R&D is underway to reduce layer thickness. These devices are more radiation resistant than CCDs and have an excellent signal to noise ratio. Hybrid active pixel sensors (HAPS) provide very fast timing information (25 ns) and are very radiation hard, but have very high power consumption, large material budget, and poor point resolution. Depleted Field Effect Transistors (DEPFET) are another alternative, pioneered by MPI-Munich.[7] Thinned devices of only 50 μm have been manufactured.

Although the general concept and performance goals are agreed upon, the specific technology choice has yet to be decided. Pixel detector R&D, underway in Europe[8] and Asia[9], will need to continue for several years to develop full size prototype ladders. If multiple technologies are successful, then the material budget (or possibly the financial budget) could be the deciding factor. In this case, detailed designs, including mechanical support, readout, and cooling will be required in order to compare the options.

3 Central Tracker

The general requirements for the central tracker is that it provide excellent momentum resolution, excellent pattern recognition and 2 track resolution, and be tolerant to high machine backgrounds. The goal for the full tracking system is to have momentum resolution of:

$$\delta(p^{-1}) \approx 5 \times 10^{-5}\ \mathrm{GeV}^{-1}$$

so as to not compromise the dilepton recoil mass resolution for $e^+e^- \to ZH$ events and end-point measurements for some super-symmetric decay chains. The requirement for good pattern recognition is demonstrated in Figure 2, which shows the complexity of a typical event in the central tracking region at a linear collider experiment.

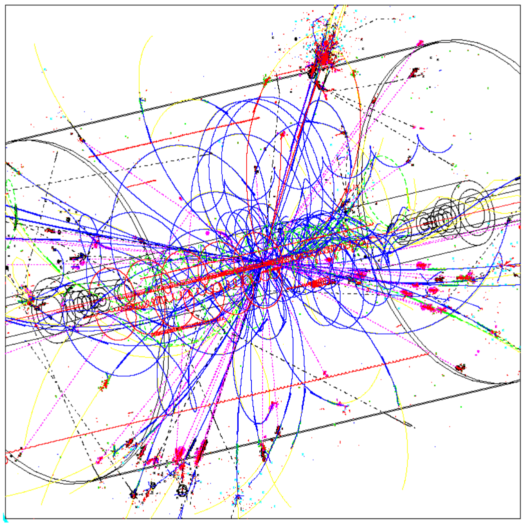

Figure 2 A typical linear collider event as observed by the central tracking system.

Unlike the situation for the vertex detector, consensus has not yet been reached on fundamental issues for the central tracker concept. The sensitive medium could be gas, which would provide many coarse measurements along the track, or silicon, providing fewer but very precise measurements. For each of these options, there is a choice to measure either 2D or 3D points. In case of gas detectors the choice is between a drift chamber or time projection chamber; for silicon detectors the choice is between a silicon strip or silicon drift designs. Detector R&D is underway worldwide to better understand the relative merits of these different techniques.

The Asian group specifies a drift chamber for its detector concept. They use a small jet cell design with alternating axial and stereo layers. A particular challenge arises from the gravitational sag of the long wires. They have built a 4.6 m long prototype chamber thereby demonstrating the ability to achieve good point resolution in a chamber with such long wires.[10]

The baseline designs for the European and North American detectors call for a large time projection chamber for the central tracking. These detectors have been limited in their resolution due to $\mathbf{E}\times\mathbf{B}$ distortions near the wire grids used for gas amplification. By replacing these grids with micropattern gas detectors (MPGDs), such as gas electron multipliers or micromegas detectors, this limitation should be removed. Since signals produced in these devices are narrower and faster, MPGD TPCs should have improved two particle separation. The number of positive ions that enter the drift volume is also expected to be reduced. Prototype TPCs using MPGDs have been built in Europe[11] and North America[12] to demonstrate the capability of these devices. Superconducting magnet facilities at Saclay[13] and DESY[11] (2 and 5 Tesla respectively) are being prepared in order to study the performance of these MPGD TPCs in magnetic fields.

A second North American detector design has a 5 layer all-silicon tracker, arranged in cylindrical layers about 25 cm apart in the central region ($|\cos\theta| < 0.8$) and as disks in the forward region ($0.8 < |\cos\theta| < 0.99$).[14,15] In order to not compromise the momentum resolution for lower momentum particles the silicon layers need to be thinned to perhaps 200 μm. Detector R&D is required to understand how to achieve such thin detectors, how best to support them, power them, and read them out. Another important issue requiring significant study is pattern recognition. Figure 3 graphically demonstrates the challenge in reconstructing a typical linear collider event with 5 layers of precise hits.

To make a well informed choice of the central tracking technology will require

- demonstrated performance in large scale prototypes in cosmic ray and test beams studies, including tests in magnetic fields
- detailed simulations of realistic detectors
- well tuned pattern recognition and track fitting programs
- comparison of performance for several key physics measurements with machine backgrounds

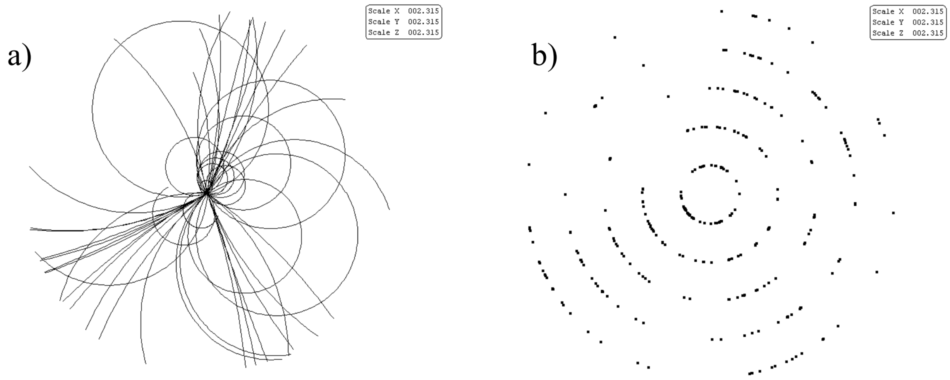

Figure 3 A graphical demonstration of the pattern recognition challenge for a typical linear collider event. a) Tracks are shown projected into the plane transverse to the beam direction. Gas detectors sample more than 100 radial positions and therefore can provide an image similar to this. b) The same event as sampled by only 5 radial layers. For an all-silicon tracker, the challenge will be to reconstruct the image shown on the left with the limited, but very precise information shown on the right. The addition of machine background hits will further complicate the process.

If no technology stands out as the clear choice once this program is completed, the most conservative choice will probably be chosen.

Specialized detectors for intermediate and forward tracking are envisaged for the gaseous tracking systems.[16,17] These include systems between the vertex and central tracker, and between the central tracker and the calorimeters. By adding a few precise points far from the vertex, these detectors, possibly in the form of silicon strips, can improve the overall momentum resolution and track finding efficiency. Bunch tagging could be made possible by using scintillating fibers. Forward tracking, outside the acceptance of the central tracker, is particularly important to measure the luminosity spectrum.[18,19,20] Significant effort is needed to make detailed designs of these detectors including their support, readout, and cooling, in order to understand the real benefit that the various components can bring to the linear collider detector.

4 Calorimeter

The general requirements for the calorimetry is that it be hermetic, have excellent jet energy and angular resolution, be able to reconstruct non-pointing photons, and have good time resolution. Of these, the issue that is most influencing the calorimeter design is the jet energy resolution.

An important goal is to be able to distinguish W and Z decays in their hadronic modes, in the absence of kinematic constraints. In order to reach a satisfactory level of separation requires the detector to achieve jet energy resolution of about 30% $\sqrt{E}$ [GeV].[21] Other studies have indicated that the resolution degradation from 30% $\sqrt{E}$ to 60% $\sqrt{E}$ is equivalent to about 40% reduction in luminosity.[21]

When kinematic fits are not possible, energy flow algorithms give the best jet energy resolution. This technique uses the tracking detectors to measure the energy of charged particles, which make up 65% of the typical visible jet energy, the electromagnetic calorimeter to measure photons (25%), and the electromagnetic and hadronic calorimeters for the neutral hadrons (10%). To understand the achievable energy resolution, a simple exercise in error propagation is helpful.[22] The total uncertainty can roughly be expressed as:

$$\sigma^2_{E\text{jet}} = \sigma^2_{E\text{charged}} + \sigma^2_{E\text{photons}} + \sigma^2_{E\text{neut.had.}} + \sigma^2_{\text{confusion}} \; .$$

The last term represents the additional uncertainty that arises from the overlapping of showers from charged particles, photons, and neutral hadrons in the calorimeter that prevents the 3 particle types to be treated separately. Values for the first three terms are approximately,

$$\sigma^2_{E\text{charged}} \approx \left(5\times10^{-5}\right)^2 \sum \frac{E^4_{\text{charged}}}{\text{GeV}^2} \approx \left(0.02\,\text{GeV}\right)^2 \tfrac{1}{10} \sum \left(\frac{E_{\text{charged}}}{10\,\text{GeV}}\right)^4$$

$$\sigma^2_{E\text{photons}} \approx \left(0.11\right)^2 \sum \left(E_{\text{photon}} \cdot \text{GeV}\right) \approx \left(0.6\,\text{GeV}\right)^2 \frac{E_{\text{jet}}}{100\,\text{GeV}}$$

$$\sigma^2_{E\text{neut.had.s}} \approx \left(0.40\right)^2 \sum \left(E_{\text{neut.had.}} \cdot \text{GeV}\right) \approx \left(1.3\,\text{GeV}\right)^2 \frac{E_{\text{jet}}}{100\,\text{GeV}}$$

where the last terms show a coefficient multiplying a term of order 1. It is interesting to see that the dominant of these three terms arises from the measurement of neutral hadrons, which make up only 10 % of the visible jet energy, typically. The best energy flow measurements yield resolution of order 30 % $\sqrt{E}$. Ignoring the negligible tracking term gives,

$$\sigma^2_{E\text{jet}} \approx \left(0.14\right)^2 \left(E_{\text{jet}} \cdot \text{GeV}\right) + \sigma^2_{\text{confusion}} \approx \left(0.3\right)^2 \left(E_{\text{jet}} \cdot \text{GeV}\right)$$

so it is apparent that the confusion term is by far the largest contributor to the jet energy resolution.

A number of ideas have been applied to reduce confusion of showers in the calorimeters. The large magnetic field and large calorimeter inner radius helps separate particles before they enter the calorimeter. The use of materials with small Moliere radius further reduces shower overlap. Figure 4 compares the same event as observed by a tungsten calorimeter with an iron calorimeter. Finely segmenting the calorimeters in all three dimensions helps algorithms separate contributions from neighouring showers. The material in front of the calorimeter should be minimized and in particular, the magnet coil should be outside of the calorimeters. The design should also be without cracks.

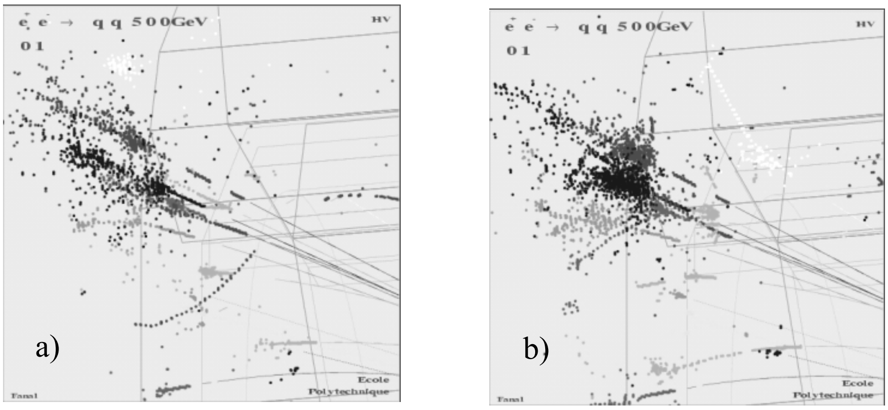

Figure 4 Comparison of showers from same event as observed in (a) a tungsten calorimeter and (b) and iron calorimeter.[21] The increased shower overlap in the iron calorimeter is apparent.

The electromagnetic calorimeter design concepts with the highest granularity are silicon tungsten.[23] These take advantage of the small Moliere radius of tungsten (9 mm). To maintain a small Moliere radius, the readout gaps between tungsten layers need to be kept at a minimum. For example, with 2.5 mm gaps and 2.5 mm tungsten layers (0.7 X_0), the Moliere radius of the calorimeter doubles. Transverse segmentation of 5 mm – 15 mm with 20 – 40 longitudinal layers are being considered. A sophisticated readout network is required in order to reduce the costs for the electronics for the 50 million pads. The total amount of silicon in such a detector is about 2000 m^2, significantly more than even the LHC detectors. Projections based on an exponentially falling silicon costs, suggest that this large amount of silicon may become affordable in several years time.[24]

For the best jet energy measurements, energy flow algorithms also need fine segmentation in the hadron calorimeter.[25] The optimal transverse segmentation is approximately given by the radiation length of the absorber material, i.e. 4 mm for tungsten and 18 mm for iron. To reduce the cost, a single bit ADC is all that is required, and thus the device is called a digital calorimeter. The readout technology under consideration includes resistive plate chambers, gas electron multipliers[26], and scintillator[27].

CALICE is worldwide collaboration of over 100 members that has formed to study fine grained calorimetery for the linear collider. They have set a goal to build a 1 m^3 prototype for beam tests in 2004.[28]

Although the arguments in favour of a highly segmented calorimeter are quite compelling, there is not yet complete consensus on this issue. Other calorimeter technologies under consideration include, lead/scintillator tile[29], crystal[30], and Sashlick calorimeters. The lead/scintillator design proposed by the Asian group is made to be compensating by using a 4:1 mix of lead/scintillator. The design has 5 cm transverse segmentation for 3-4 layers, for the inner electromagnetic part, and 20 cm transverse segmentation for the out hadronic part. The effect of the coarser segmentation of this design on energy flow algorithms needs to be quantified. One of the major challenges for such designs is the low light yield in small cells and the difficulty to read these out in the presence of large magnetic fields.

The LCcal collaboration is considering a hybrid design, mixing lead/scintillator tiles with 3 planes of silicon.[31] They plan to build a prototype for test beam studies. A Europe-Russia tile HCAL collaboration also plans to build a prototype for beam tests in 2004.[32]

Less attention has been paid to the forward calorimeter concept. These detectors play an important role in defining the absolute luminosity and the luminosity spectrum, as well as providing hermiticity necessary for discovering new final states with significant missing energy.[33]

In summary, consensus has not yet been reached on the fundamental design of the calorimeter. In recent years, the effort on designs optimized for energy flow algorithms have grown. A very strong case needs to be made, however, for the large cost increment for these highly segmented detectors. The different designs need further simulation studies, beam tests to verify the simulations, development of even more clever algorithms, and head to head comparison of performance in key physics measurements.

5 Muon and Hadron Identification

The muon system for a linear collider detector can likely directly apply the techniques used in existing detectors.[34] The system would cover a large area, some 4 – 7000 m^2 for about 6 – 12 layers and about 1.5 m of iron absorber would be necessary. Due to the large magnetic field, the system would only be efficient for transverse momentum above 5 GeV. A point resolution of about 1 cm is required, and therefore resistive plate chambers or scintillators could be used.

As yet no important physics processes have been identified that demand excellent particle identification at the linear collider experiment.[35] The *dE/dx* energy loss measured by gaseous trackers can provide good π – K discrimination, without introducing additional material. A dedicated hadron identification device appears to be unwarranted.

6 IP Beam Instrumentation

There are a number of detectors that are concerned with defining the initial state properties. Whereas the luminosity spectrum and scale are probably best done by the forward tracker and calorimeter, the absolute beam energy and polarization need dedicated detectors, physically separate from the linear collider detector. The responsibilities for these special detector items, however, will still lie in the hands of the experimental physicists, and thus these elements should be considered as an extension of the linear collider detector.[36]

The most demanding physics requirement for accurate absolute beam energy measurements comes from *WW* threshold scans, where about 5 MeV resolution is necessary, about 50 parts per million. For top threshold or Higgs mass determination, only 50 MeV (about 200 ppm) is required. Spectrometers based on synchrotron light, as was done at SLC, or beam position monitors, as was done at LEP, are under consideration. Moeller scattering or the measurement of radiative returns to the *Z* pole are possible alternatives.

Beam polarization measurements accurate to 0.1% are necessary to measure various standard model asymmetries, especially should a large sample of data be collected near the *Z* pole. For the background suppression of WW events, only 1% precision is necessary, and for analysis of supersymmetric particles requires only 0.5% precision. Dedicated instruments to measure polarization can be based on Compton scattering, as was done at the SLC, or Moeller scattering. Alternatively, the linear collider detector itself can be used, by using the WW process itself. This would account for all beam-beam effects automatically, but would be statistics limited and implicitly assumes the Standard Model to be correct.

7 Summary

The initial concepts for a linear collider detector are now well established. Significant effort is continuing in detector research and development. These studies are refining the basic ideas for the detectors, proving the validity of specific designs, and help to develop alternative concepts. This work is essential now, in order to be able to make the right decisions in the (near!) future.

Detector performance goals have been set by important physics processes that we expect to observe. We should, however, not disregard opportunities to exceed the goals. We all hope that a big part of the actual linear collider physics program will be completely unexpected. The extra capability built into the detector may turn out to be critical to understand the new phenomena. Capabilities such as photon pointing and hadron identification may fall into this category.

It is encouraging to see that much of the detector research and development effort are being done as international collaborations. These groups are the seeds for the future collaboration that will be charged to design and build the detector for the linear collider. I have no doubt that we will be ready to undertake this mission in the next few years.

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