

# Research and Development towards a Detector for a High Energy Electron-Positron Linear Collider

Bruce A. Schumm\*

*Santa Cruz Institute for Particle Physics and the University of California, Santa Cruz*

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This exposition provides a detailed picture of ongoing and planned activities towards the development of a detector for a high-energy Linear Collider. Cases for which research and development activity does not exist, or needs to be bolstered, are identified for the various subsystems. The case is made that the full exploitation of the potential of a high-energy Linear Collider will require the augmentation of existing detector technology and simulation capability, and that this program should become a major focus of the worldwide particle physics community should the construction of a Linear Collider become likely.

## I. INTRODUCTION

Over the decade of the 1990's, the five LEP and SLC detectors made numerous precise measurements of Standard Model couplings and parameters. Because of this, and the relative cleanliness of  $e^+e^-$  beam collisions, there is a tendency to think that designing and building a detector for a high-energy (TeV range)  $e^+e^-$  Linear Collider (LC) should be relatively straightforward, requiring an R&D program of a scale much smaller than that of its hadron-collider counterparts. There are a number of reasons to question this point of view.

Although it has been shown that the LC does have unique discovery potential relative to the LHC, the physics case for the LC is predicated largely on its ability to complement discoveries made at hadron colliders with comprehensive and precise measurements. Over the last few years, it has become increasingly clear that the full exploitation of the potential of the LC to do these exacting studies places demands on the design of a LC detector which can not be met with existing experimental approaches.

For example, the determination of the light Higgs branching fractions, in particular into  $c\bar{c}$  pairs, benefits from a tracking system with substantially better vertexing (for flavor identification) and momentum resolution (for recoil mass-peak cleanliness) than that of existing detectors. The desire to reconstruct  $W$  and  $Z$  bosons via their hadronic decays places stringent demands on the performance of the calorimeter system, suggesting innovative approaches allowing energy-flow reconstruction, with the requirement of a large volume of minutely segmented calorimetry, and a correspondingly large number of channels. No longer a purely  $s$ -channel machine, the LC community will also need to think very hard about robust instrumentation for the far forward region (200 mrad and below). Finally, the possibility of a fully open trigger, in which all beam crossings are read out, provides an interesting challenge for electronics and software efforts, while allowing a number of interesting physics capabilities. In all of these cases, the full capabilities of the LC can not be exploited with existing technology.

Underlying all of these potential technological pursuits lies a common question: that of whether or not the effort and expense engendered by each individual development project is justified by the potential physics gain. This set of questions can only be answered via a vigorous program of realistic simulation study. It seems imperative that existing simulation efforts be substantially enhanced, with the thought in mind that the simulation results should inform and focus the hardware R&D program.

## II. THE NOMINAL LINEAR COLLIDER DETECTORS

There are currently four cylindrical-geometry detector scenarios under consideration for the TeV-scale Linear Collider (a fifth, so-called 'Precise' detector under consideration for a moderate-energy IP will not be discussed here)[1]. All four detector schemes incorporate a precise pixel-based stand-alone inner tracker to accurately reconstruct charged track impact parameters. Precise momentum and angular resolution is provided by a large-volume central tracker, implemented either as a drift chamber ('DC'; the Asian, or 'JLC' design), a time-projection chamber ('TPC'; the TESLA and North American 'L' designs), or a larger area solid-state tracker

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\*schumm@scipp.ucsc.edu; <http://scipp.ucsc.edu/~schumm>

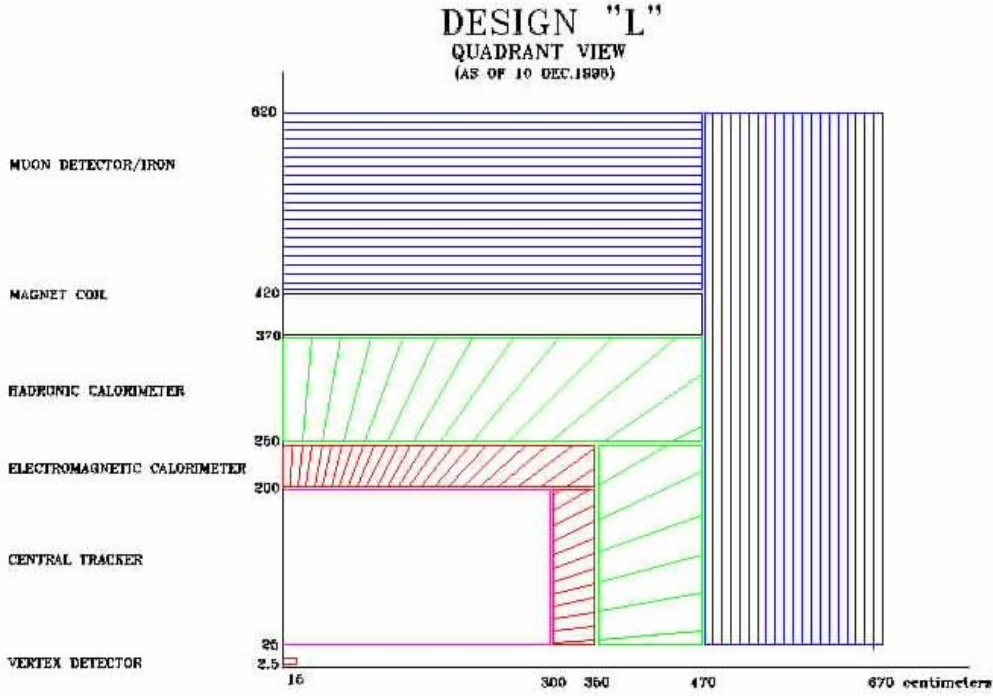


FIG. 1: Schematic of the North American Large ('L') Detector Design

('SST'; North American 'SD' design). The radius of the first sensitive layer varies from 1.2 cm (L, SD) to 2.4 cm (JLC), while the full tracking systems are immersed in axial magnetic fields of between 2 (JLC low-field option) and 5 (SD) Tesla.

Proposed electromagnetic calorimeter solutions include either a highly-pixelated silicon-tungsten sandwich design (TESLA and SD), or a lead-scintillator sandwich design (JLC, L). The TESLA collaboration is also considering a Shashlik option. Proposals for hadronic calorimetry include lead-scintillator (JLC, L, SD), and iron-scintillator (TESLA). TESLA has also recently introduced the notion of 'digital' hadronic calorimetry, for which showers initiated in the iron absorber material would be read out in terms of a simple yes/no response from highly segmented ( $\sim 1 \text{ cm}^2$ ) gas chambers.

Forward tracking systems with coverage down to approximately 100 mrad are envisioned for the TESLA, L, and SD detectors, with silicon-strip disks being the most likely technology. Forward tagging calorimetry down to 30 mrad or less is envisioned in all cases, with possible implementations including silicon-diamond and an innovative solid-state '3-D Pixel' design.

Figure 1 shows a schematic of the North American L detector, typical of the proposed designs.

### III. TRACKING

The motivation to improve the precision of charged-particle tracking for Linear Collider detectors has been driven by several factors. To begin with, the need to do flavor – and particularly charm – separation has driven a push towards more precise impact parameter reconstruction and vertexing. For example, the prospect of a light Higgs motivates an interest in the absolute  $H \rightarrow c\bar{c}$  branching fraction, while the effective luminosity of the study of symmetry breaking via strong coupling between longitudinal  $W$  boson states can be enhanced by a factor of two or more via the use of a clean tag of charm in the  $W$  decay jet. In both of these cases, the impact parameter performance of existing vertex detectors would not be adequate to extract the full physics capabilities of the Linear Collider.

In addition, in order to identify the Higgs signal, and constrain the Higgs width, the reconstruction of the missing-mass spectrum from the critical channel  $e^+e^- \rightarrow ZH$ ;  $Z \rightarrow \mu^+\mu^-(e^+e^-)$  should not degrade the 0.2% width expected from the beam energy spread. In addition, the dilepton mass resolution should be small compared to the natural width of the  $Z$ , even at the large  $Z$  kinetic energies that will be associated with this 'Higgstrahlung' process at the highest achievable machine energies. This requires that the overall momentum of individual tracks be reconstructed with an accuracy approaching  $\delta p/p^2 \simeq 1 \times 10^{-5}$ , representing an improvement

## Suggested layout of Vertex Detector for future $e^+e^-$ Linear Collider (Updated November 1998)

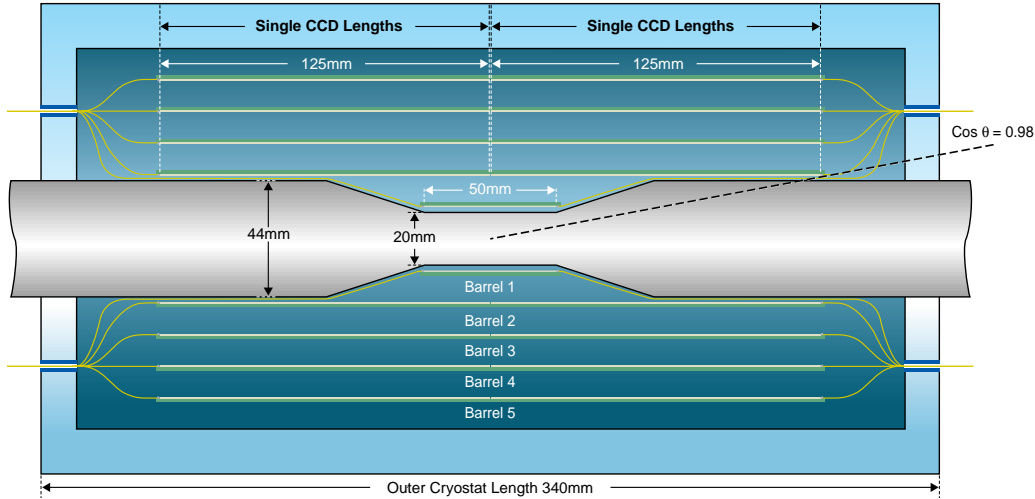


FIG. 2: Design schematic for the common TESLA and North American Linear Collider Vertex Detector.

of over an order of magnitude relative to existing  $e^+e^-$  detectors. While a large portion of the improvement is expected to come from increasing the strength of the magnetic field, achieving this degree of accuracy will also require a large radial lever arm, good single-hit resolution, and careful attention to alignment and calibration systematics.

### A. Precision Vertexing

The SLD VXD3 [2] vertex detector has set the current standard for precision tracking at  $e^+e^-$  colliders, and the common VXD design for the TESLA, L, and SD detector scenarios are essentially an outgrowth of that successful design. The Linear Collider VXD design, shown in Figure 2, is a pixel based stand-alone tracking system with five layer coverage to  $|\cos \theta| = 0.87$  and single-layer coverage out to  $|\cos \theta| = 0.98$ . It is expected to achieve an  $r - \phi$  impact parameter resolution at high momentum of better than  $3 \mu\text{m}$ , with a multiple scattering term of less than  $10 \mu\text{m}$  at  $p_\perp/\sqrt{\sin \theta} = 1 \text{ GeV}/c$ . Both of these are substantially better than those achieved with the SLD VXD3, as can be seen in Figure 3.

The baseline VXD design is instrumented with  $20 \times 20 \mu\text{m}^2$  CCD pixels, demanding approximately  $7 \times 10^8$  pixels, only about a factor of two greater than that of the existing VXD3 detector of the SLD. However, due to the need to maintain signal efficiency over the large number of transfers from the struck pixel to the readout pad, CCD's are relatively sensitive to radiation damage. For expected neutron fluences of order  $10^9 \text{ cm}^{-1}$ , the charge-transfer efficiency becomes significantly compromised by the development of traps. It has been shown [3] that filling these traps, for example with carriers released in response to a flash of light, largely restores the charge-transfer efficiency for a period approaching one second. While an encouraging proof of principle, this notion needs to be engineered into a working solution.

The greater luminosity of the TeV-scale Linear Collider will require an increase in readout rate from 5 to 50 MHz, in order to maintain the CCD occupancy low enough that it will not compromise the physics at a 120 Hz JLC/NLC. For TESLA, however, integrating over the several thousand crossings of the  $800 \mu\text{s}$ -long TESLA bunch train will lead to prohibitive occupancy in the CCD's, even with 50 MHz readout. Thus, the design is underway for a CCD sensor which will allow parallel readout of the individual detector columns ('column-parallel' readout), allowing the detector to be read out many times during the  $800 \mu\text{s}$  spill.

The VXD baseline design calls for a ladder thickness of  $0.12\% X_0$  or thinner – a substantial reduction from the  $0.4\% X_0$  achieved for the SLD VXD3. Achieving this goal will require the ladders to be supported from the ends only; substantial work is getting underway to explore the design and stability of appropriate support systems. In addition, it may be possible to improve upon the  $3 \mu\text{m}$  single-hit resolution that has already been achieved with  $20 \mu\text{m}$  CCD pixels. Again, the motivation for these various R&D paths needs to be provided via the simulation of physics channels which may depend upon them. Finally, while a substantial and formal R&D

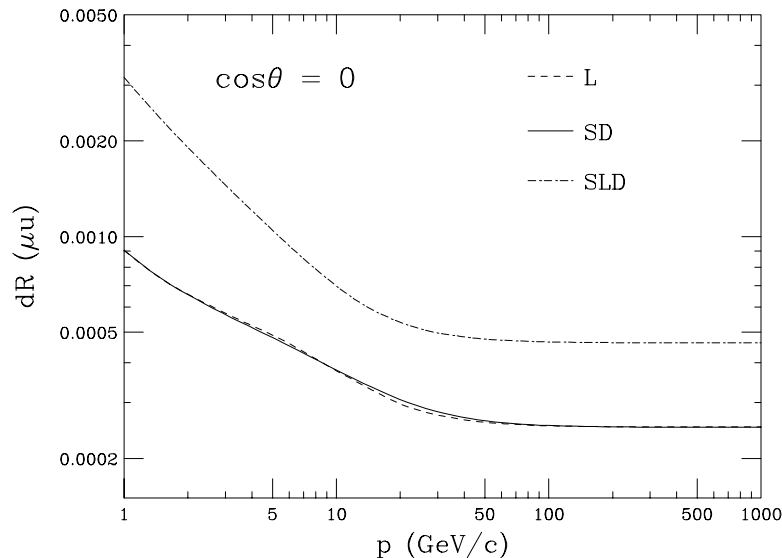


FIG. 3: Impact parameter performance of the Linear Collider Vertex Detector. To the extent that the momentum resolution is similar, this performance is independent of the choice of central tracker (TPC for ‘L’ versus solid-state for ‘SD’). The performance of the former SLD system is shown for comparison.

task force already exists (the UK Linear Collider Flavour Identification Collaboration), the amount of work to be done towards a final design is substantial, and is by no means saturated by this group.

An interesting alternative to CCD pixels, particularly if the radiation damage or readout issues turn out to be insurmountable, is that of monolithic CMOS pixel detectors[4]. Rather than having the local electronic circuitry bump-bonded to the pixel sensors, as for conventional fast pixel detectors, the first-stage readout is deposited directly onto the sensor wafer, allowing for a much thinner structure than that of standard active pixel arrays. In addition, the monolithic approach seems fairly promising in terms of achieving the small ( $20 \mu\text{m}^2$ ) pixel dimension required to avoid problems with cluster merging at the TeV-scale Linear Collider. The active pixel group at IReS Strasbourg is developing a monolithic sensor for which a local array of three transistors will amplify and drive signals from  $20 \times 20 \mu\text{m}^2$  pixels, which can be read out individually via shift-register controlled column and row selectors. Test beam results with early prototypes suggest high hit efficiency ( $\sim 99\%$ ) and good resolution ( $\sim 1 \mu\text{m}$ ). Issues being addressed with current development work include the development of large-scale (detector-sized) arrays, system and integration issues, and radiation hardness.

## B. Central Tracking

Proposals for LC central tracking systems fall into two main categories: gaseous and solid-state. Proposals for gaseous tracking systems include a large-volume TPC (TESLA and North-American L), and a mini-jet-cell drift chamber with a longitudinal extent of greater than 4 meters (JLC). The North-American SD design calls for a large-area solid state tracker, implemented either with silicon strip or silicon drift technology. A substantial R&D effort is called for in order to develop and optimize each of these systems for the LC detector.

The Japanese drift chamber development program has been driven primarily by the chamber length, as well as the large magnetic field needed to achieve a resolution of  $\delta(1/p_\perp)$  of  $10^{-4}$ . They have addressed issues associated with electrostatic and gravitational wire sag, stereo wire geometry, wire tension loss, and the large Lorentz angle. Understanding the sensitivity to LC backgrounds, including neutrons, is a critical issue that still needs to be addressed.

A sizable collaboration, mostly European but also including several North American institutions, is exploring the use of a large-volume TPC at the LC. The TPC enjoys several nominal advantages over a conventional drift chamber, including true three-dimensional track measurements to help disentangle dense jets, as well as a high degree of pixellation to reduce sensitivity to LC backgrounds. The goal of  $\delta(1/p_\perp) \simeq 5 \times 10^{-5}$  places substantial demands on the spatial resolution of the endplate readout, as well as its ion feedback suppression capability. In addition, alignment tolerances must be maintained to several microns – substantially better than that of existing TPC’s – requiring the exploration of calibration and environmental control techniques.

A large effort is currently focussed on the development of micro-pattern gas detector technology (GEM and

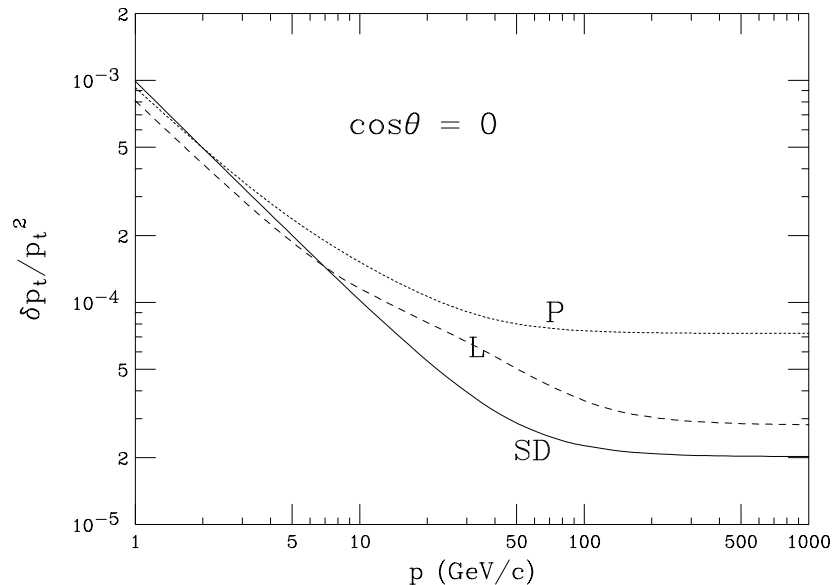


FIG. 4: Momentum resolution versus momentum at  $\cos\theta = 0$  for various North American detector designs (the performance of the TESLA and Asian designs are similar). P = Precise; L = Large; SD = silicon.

MicroMEGAS), which would provide an alternative to the standard MWPC readout systems. Studies suggest that optimized readout pad structure will admit appreciable improvements in both the single-hit and two-track resolution relative to those of the MWPC readout. In addition, the natural ion feedback suppression of micro-pattern detectors may allow the elimination of the gating grid, and the corresponding need to run the TPC in a triggered mode.

A number of other R&D issues are being explored for the TPC option. The gas mixture is being studied in order to optimize tradeoffs between resolution versus ion clearing, and quenching versus neutron background susceptibility. The emphasis on LC physics in the forward region is somewhat new for  $e^+e^-$  detectors, and thought must be given to minimizing the thickness in the endplate region. Finally, the high degree of spatial and temporal pixellation desired for the TPC readout provides a challenge to the development of fast multichannel electronics.

Both silicon-strip and silicon-drift are now mature tracking technologies, an example of a system composed of the latter being the STAR collaboration's silicon vertex detector[5], for use in studying charged tracks from heavy ion collisions at RHIC. The baseline design of the North American SD detector calls for five cylindrical layers of solid-state tracking with radii between 20 and 125 cm, and a polar angle coverage of  $|\cos\theta| \leq 0.8$ . Either option (strip or drift) seems applicable to such a design, although again a substantial R&D program would be required in order to optimize the design of either.

A nominal advantage of solid state over gaseous tracking arises in the context of background immunity, due to the fact that the energy deposition of low-energy gamma conversions is very localized in the dense silicon. In the case of silicon drift, the detector is intrinsically three-dimensional (due to the drift of the liberated conduction electrons in the  $z$  direction), leading to further reduction of background sensitivity via the correspondingly fine pixellation.

Two mutually exclusive approaches have been proposed for the design of the SD silicon strip detector. With the development of short shaping-time readout, it may be possible to time-stamp silicon strip hits with a resolution of as little as 5 nsec, leading to a corresponding increase in the ability to select against LC backgrounds. On the other hand, long shaping-time readout offers the possibility of long, thin detector ladders which can be read out without introducing electronics into the detector fiducial volume, leading to superior  $p_t$  resolution even at low momentum. In addition, the large (125 cm) radial lever arm and high (5T) field of the SD detector yield, assuming an  $r$ - $\phi$  resolution of  $7 \mu\text{m}$ , a resolution in  $\delta p_t / p_t^2$  approaching  $2 \times 10^{-5}$ . A comparison between the North American L, SD, and P detectors (the latter not discussed here) of the momentum resolution vs. momentum, at  $\cos\theta = 0$ , is shown in Figure 4.

A number of other hardware issues more or less common to both solid state detector options need to be addressed. If the low LC collision duty cycle can be taken advantage of by the readout electronics, it should be possible to manage local power consumption with passive cooling. The development of a frequency-scanned

interferometric alignment system for the ATLAS inner detector[6] suggests that the maintenance of such tolerances are within reach of current technology. The effects of the large magnetic field on the drift of electrons and holes must be understood and controlled. Finally, comprehensive radiation damage studies need to be conducted, in order to ensure that the proposed solid state detectors (particularly for the case of silicon drift) can withstand LC backgrounds.

### C. Forward Tracking

Much of the interesting physics at a high energy LC is not produced via the  $s$  channel, and as such tends to be boosted into the far forward or backward regions of the detector. Thus, substantially more emphasis needs to be given to these regions of the detector than was for the case of the  $Z^0$ -pole  $e^+e^-$  detectors. The forward tracking system needs to maintain good momentum resolution for the accurate measurement of the slepton spectrum endpoint, and fractional resolution of the dip angle approaching one part in  $10^4$ , in order to appropriately constrain the differential luminosity spectrum via the asymmetry in radiative bhabha events.

The North American designs have preserved momentum resolution of better than  $\delta p_t/p_t^2 = 7 \times 10^{-4}$  out to  $\cos\theta = 0.99$  with a system of silicon-strip  $r$ - $z$  disks. The TESLA design improves this to  $\sim 2 \times 10^{-4}$  with an additional fine-grained forward tracking chamber (FCH) just beyond the TPC endplate. Little effort has been put into the design of forward tracking systems other than the optimization of the overall detector geometry that can be done with closed-form track parameter error calculations. The detailed design and integration of a precision forward tracking system that can withstand the low-angle LC backgrounds remains a wide-open and critical R&D issue in the development of the LC detector.

### D. Tracking Simulation Issues

Substantial thought has been put into the proposal of approaches that minimize tracking resolution parameters, with the goal of producing a LC detector design that can exploit the intrinsic precision available from high energy  $e^+e^-$  collisions. While some simulation work has been done to explore the extent to which tracker parameters, such as point resolution, radial lever arm, and material burden, need to be pushed in order to exploit LC physics, much work still remains to be done. Eventually, choices between detector technology, or of whether or not to pay for an incremental improvement in a given technology, will need to be based on a concrete assessment of the physics advantage to be gained.

Studies underway to understand the impact of vertexing parameters such as point resolution, layer thickness, and inner radius on the measurement of the Higgs branching fraction and strong  $WW$  scattering parameters need to be brought to fruition. Detailed studies of the dependence of the selectron mass measurements on the forward tracking resolution need to be undertaken. Physics channels need to be simulated which will establish targets for the polar angle resolution necessary to perform the differential luminosity spectrum. Targets for transverse momentum resolution, both a low and high momentum, need to be established in order to inform R&D programs directed at lessening the material burden and improving the accuracy of the sagitta measurement.

Thought should also be given to the advantage of having  $dE/dX$  information, which would be of higher quality for a gaseous tracker. While  $\sim 10$  layers of silicon (vertexer plus SD central tracker) do provide a reasonably accurate energy loss measurement, the density effect limits the differentiation between particle species in the relativistic rise region. Thus, for relativistic electrons which do not reach the calorimeter,  $dE/dX$  information from a gaseous tracker may well be the only to provide separation from pions. The extent to which the consideration of  $dE/dX$  resolution is relevant to the design of the LC detector is an issue that needs to be addressed by the simulation effort.

While the aforementioned issues are probably best addressed with a fast simulation, a number of more detailed questions can only be addressed with a full-scale detector simulation and realistic reconstruction. Concerns that the limited number of widely spaced hits from a solid state tracker might compromise the ability to distinguish closely spaced tracks in collimated jets, or to detect the decay kinks of long-lived exotic states, need to be addressed with this more realistic simulation. Another interesting question that can be addressed with the full simulation is the need for a central tracker with intrinsically three-dimensional tracking, such as that provided by a TPC or silicon drift detectors, in view of the ultra-fine vertex detector pixellation. No study has been done as of yet regarding the relative track-separation resolutions of the various proposed solutions. The value of temporal pixellation, in regards to background suppression, needs to be explored, as does the value of an intermediate silicon tracker in the gaseous detector options. Finally, the entire issue of the interplay between the tracker and calorimeter, in terms of backplash into the outermost layers, as well as optimizing the energy flow measurement (to be discussed below), remains to be explored with the full simulation.

TABLE I: Measurement of the components of high energy jets

Component	Measurement
Neutral pions	$\sim 15\%/\sqrt{E}$ in EMCAL
Photon	$\sim 15\%/\sqrt{E}$ in EMCAL
Charged hadrons	$\sim 0.1\%$ in tracker
Charged leptons	$\sim 0.1\%$ in tracker
Stable neutral hadrons	$\sim 40\%/\sqrt{E}$ in HADCAL
Neutral leptons	No measurement

#### IV. CALORIMETRY

Precise, hermetic, full-coverage calorimetry is thought to be a must for a LC detector. The ability to make precise jet energy measurements for hadronic final-state reconstruction, to have a discriminating tool for electron-pion separation, and to perform measurements of neutral particle trajectories with a precision approaching that of a crude tracking system, seem to be desirable goals for the LC detector calorimeter design. Accumulated wisdom suggests that the way to accomplish this is with ‘energy-flow’ calorimetry.

The idea behind calorimetric energy-flow measurement is encapsulated in Table I. All components of hadronic jets are well-measured except a relatively small fraction of stable neutral hadrons (mostly  $K_L$  and neutrons). If the calorimetric energy deposits from charged hadrons can be removed from the jet, and replaced with the amply precise tracking measurement, overall jet energy resolution can approach that of the main remaining calorimetric component, which is electromagnetic and thus relatively well-measured. Clearly, achieving this goal places stringent requirements on the track-cluster association capabilities of the combined calorimeter and tracking system.

Toy MC studies[7] performed with a JETSET sample of  $e^+e^- \rightarrow q\bar{q}$  events indicate that, in the ideal situation that every charged hadron contributes to the jet measurement only through its tracking information, a jet energy resolution of  $18\%/\sqrt{E}$  is achieved. On the other hand, with perfect  $e/h$  compensation, and using the calorimeter only, the resulting jet energy resolution is  $64\%/\sqrt{E}$ .

Although this ideal jet energy resolution will be difficult to achieve in practice, even a resolution of  $30\%/\sqrt{E}$  will provide a significant advantage for the isolation of physics signals. An example of this – the separation of  $e^+e^- \rightarrow ZZ\nu\bar{\nu}$  from  $e^+e^- \rightarrow WW\nu\bar{\nu}$  – is shown in Figure 5. For a resolution of  $60\%/\sqrt{E}$ , the dijet mass signal region mixes the two channels together, while for  $30\%/\sqrt{E}$ , the separation of these two channels is distinct.

Generic requirements for energy-flow calorimetry include a large product of magnetic field and inner radius squared ( $BR^2$ ) to provide a large separation between charged tracks. In order to keep the calorimeter showers well contained and separated from neighboring showers, it is necessary to achieve a minimal Moliere radius, and to have the fine readout segmentation needed to take advantage of the resulting small shower spread. Frequent longitudinal sampling will allow the sharpest discrimination between electromagnetic and hadronic depositions, as well as the most precise reconstruction of the trajectory of incident charged particles (for the purpose of track/cluster matching). Finally, the tracker needs to be well integrated, so that material in the outer reaches of the tracker does not degrade the cluster-matching capabilities. The choice of technology to achieve these goals is currently focussing on a silicon/tungsten sandwich, with a readout pixellation of order  $1\text{ cm}^2$  to complement the Moliere radius of tungsten.

The greatest progress towards establishing the feasibility of energy-flow calorimetry in high-energy  $e^+e^-$  collisions has been made by the TESLA collaboration. Among other things, this work has led to a novel approach to hadronic calorimetry. With a resolution of typically  $40\%/\sqrt{E}$ , the hadronic resolution tends to dominate the accuracy of the jet energy resolution. TESLA has proposed very fine pixellation (again  $1\text{ cm}^2$ ), for an iron/gas sandwich hadronic calorimeter that is read out digitally (yes/no for each cell), as an alternative to their previous  $5 \times 5\text{ cm}^2$  iron/scintillator baseline, which would be read out in an analog mode. The idea behind this so-called ‘digital’ hadronic calorimeter is to continue from the EM calorimeter, to an extent that is economically feasible, the ability to distinguish electromagnetic sub-clusters in the hadronic shower. Incidentally, this technology would also allow muon identification below  $5\text{ GeV}/c$ , for which muons do not have enough range to traverse the calorimeter and enter the muon chambers.

Development is underway for the more conventional HCAL approach, for which the calorimeter is instrumented with  $5 \times 5\text{ cm}^2$  scintillator tiles read out via wavelength shifting fibers. The fibers are bundled to form calorimeter cells, and read out with photodiodes. The group is currently in the process of doing lab tests on several industrial alternatives for the various hardware components of the calorimeter, including the scintillator tiles, wavelength-shifting fibers, optical wrappings, and optical readout fibers. They are also exploring the

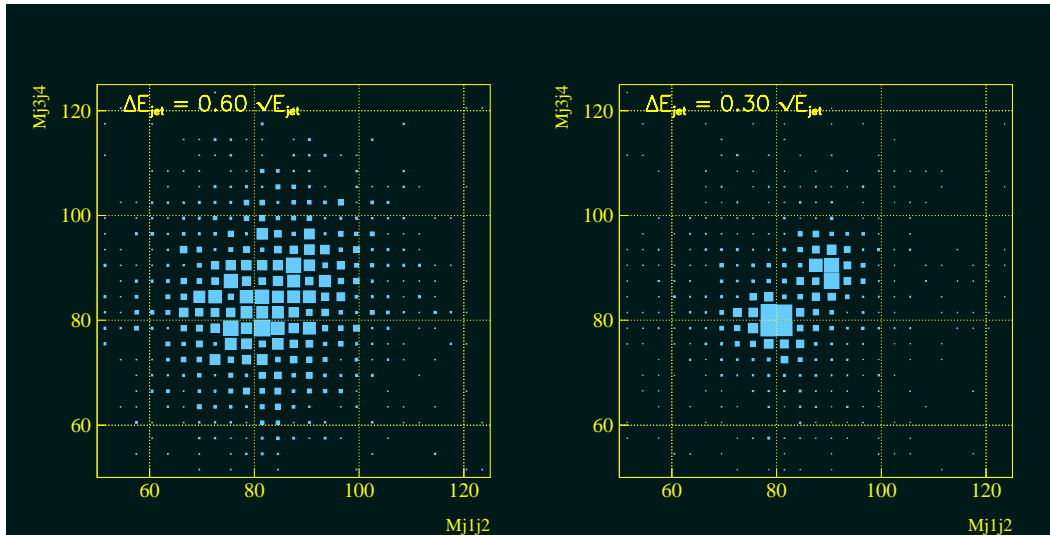


FIG. 5: Reconstruction of the jets in the processes  $e^+e^- \rightarrow Z^0Z^0$  and  $e^+e^- \rightarrow W^+W^-$  at  $E_{cms} = 500$  GeV for jet energy resolutions of  $60\%/\sqrt{E}$  (left) and  $30\%/\sqrt{E}$  (right).

optimal way to couple the scintillation light into the wavelength-shifting fibers, and transporting the light to and coupling the light into the photodiodes. The photodiode is also under development, with a 32-channel Avalanche Photodiode pixel array developed at DESY and MPI-Munich currently under study. It is expected that this process will continue through summer 2002, and will result in the construction of a 27 layer prototype ‘Minical’ for test beam studies.

A decision between these two HCAL alternatives is expected soon – perhaps as early as November, 2001 – and preliminary simulation studies have been favorable to the ‘digital calorimeter’ approach. Simulations of isolated pions entering the digital calorimeter have indicated hadronic energy resolution of  $29\%/\sqrt{E}$ , maintaining over a wide range of incident energies.

TESLA has conducted a number of interesting simulation studies on the trade-offs between cost and performance in the EM calorimeter. The EM design proposal call for 40 silicon-tungsten layers in about  $25 X_0$ . The group has found very little degradation associated with a dead-wafer fraction as high as 5%; the ability to operate with this many bad silicon wafers would relax production tolerances in a way that may save as much as a factor of two in production costs. Reducing the number of layers from 40 to 20 would yield the expected degradation of  $\sim \sqrt{2}$  (from  $10\%/\sqrt{E}$  to  $14\%/\sqrt{E}$ ) for individual electromagnetic particles. However, much of the interesting physics that would be done with calorimetric information would rely on jet rather than individual particle reconstruction, for which the fractional degradation would be much less.

In the context of jet reconstruction, simulations of the processes  $e^+e^- \rightarrow Z^0 \rightarrow q\bar{q}$  at  $E_{cm} = 91$  GeV, and  $e^+e^- \rightarrow \gamma Z^0 \rightarrow \gamma q\bar{q}$  at  $E_{cm} = 500$  GeV, have been conducted. A full-scale simulation of these processes is very involved, requiring the development and optimization of realistic track/cluster matching and energy flow algorithms. In this case, a less sophisticated approach was used, in which individual particles were reconstructed with ideal resolutions, but a parameterization of a realistic subtraction/substitution package was used to replace hadronic clusters with their tracking information[9].

For a hadronic calorimeter resolution of  $30\%/\sqrt{E}$ , these simulations indicated an overall jet-energy resolution of  $26\%/\sqrt{E}$ , a value thought to be quite interesting given the result of Figure 5. While these simulations may be somewhat ideal, it also may be that the track/cluster matching algorithm is not completely optimal. Thus, it’s difficult to say whether these results are optimistic or pessimistic. A similar study for the iron/scintillator solution found a jet-energy resolution of  $46\%/\sqrt{E}$ , although with the use of a substantially less developed track/cluster matching algorithm. Nonetheless, the simulation studies do suggest the possibility of substantially improved performance with the digital calorimeter approach. Much work – both in shoring up the simulation studies as well as presenting a design for a gaseous cell that can be read out with a pixellation of  $1 \text{ cm}^2$  – must be completed before the choice of this approach can be confidently made.

One important issue that has been raised by the TESLA group’s simulation work is a potential problem with background in the track/cluster association in the forward sections of the electromagnetic calorimeter. The source of spurious clusters seems to arise from the albedo associated with charged hadron interacting in the mask, which lies just inside the endcap calorimeter, and is used to absorb backscplash from the exiting disrupted beam as it re-enters the machine aperture. More work needs to go into these simulation studies



in order to understand how to keep these backgrounds from compromising the energy-flow capabilities of the forward calorimetry.

An alternative being considered by the TESLA collaboration, which would be particularly attractive if the advantages provided by energy-flow calorimetry are not thought to be central to the LC physics case, is a Shashlik electromagnetic calorimeter. The Shashlik design incorporates a lead/scintillator sandwich, with the scintillator read out by a wavelength-shifting fiber. Transverse pixellation of as little as  $3 \text{ cm}^2$  can be achieved, while a degree of longitudinal segmentation can be accomplished via the use of scintillator materials with different decay times. The Shashlik option offers the potential for a favorable ratio of performance to cost, although its ability to provide clean track/cluster association and trajectory information is limited relative to that of the proposed silicon/tungsten design.

The Asian study group is proposing a conventional lead/scintillator sandwich whose thicknesses in the hadronic portion are optimized for  $e/\pi$  compensation. The scintillating tiles will be read out via wavelength-shifting fibers.

The electromagnetic calorimeter is divided into three sections of  $4 X_0$  (preshower),  $9 X_0$ , and  $14 X_0$ , respectively, and with a tile dimension of  $6 \times 6 \text{ cm}^2$ . The electromagnetic calorimeter design also incorporates a  $1 \text{ cm}$  scintillator strip array a shower-max, with  $1 \text{ cm}^2$  silicon pads being maintained as an option should studies show it to be warranted. The hadronic calorimeter consists of four sections of about  $1.5 \lambda_0$  each, for a total of  $6.5 \lambda_0$ . The transverse segmentation in the hadronic calorimeter is  $18 \times 18 \text{ cm}^2$ .

The Asian group would like to achieve a two-jet resolution better than the Z-boson and W-boson widths, to avoid having the reconstruction of these states limited by detector resolution. A fast MC simulation, including the use of track-cluster association, suggests a resolution on W-boson dijets of  $2.9 \text{ GeV}$ , somewhat worse than the  $2.1 \text{ GeV}$  natural width of the W. This simulation, however, did not include the potentially advantageous use of the shower-max information.

The Asian group has conducted beam tests of their tile/fiber prototype both at KEK and FNAL. For electrons, they have found  $\sigma_E/E = (24 \pm 0.8)\%$ , while for pions they measure  $\sigma_E/E = (47 \pm 0.9)\%$ . They observed better than 1% linearity for the entire explored range between 2 and 150 GeV. Some signal loss was experienced for electrons entering near tower boundaries, which will be an avenue of further development work.

The Asian group's continued development work is focussing on a number of areas. The group is pursuing affordable means for producing reliable scintillator strips for the shower-max detector. They are also looking into a number of potential ideas for reading out the strips, including high-performance multi-channel photon detectors, or even avalanche photodiodes to read the strips out directly, without the use of wavelength-shifting light guides. They are also beginning an effort to develop a full simulation which would allow them to realistically address the study of jet-energy resolution, given the performance on individual particles observed with the test beam.

The worldwide LC calorimetry effort could benefit greatly from additional simulation and prototyping effort. While studies such as that of Figure 5 suggest that energy-flow calorimetry can be a very powerful tool indeed, they fall short of informing us of the overall programmatic advantage of implementing energy-flow capabilities in the LC detector. It would be beneficial to have a number of realistic studies of the physics reach in various essential channels as a function of calorimeter technology. In addition, should energy-flow calorimetry be thought desirable, full-scale simulation of the entire measurement system, including the interplay between the tracking system (reconstruction parameters and material burden) and calorimetry, will be necessary in order to build confidence in specific designs. Finally, prototyping of the more promising avenues should begin, so that well-founded estimates of cost and performance parameters can be developed.

## V. TRIGGERING AND ELECTRONICS

More than its energy reach, the complementarity of the LC program to that of the LHC makes the LC program interesting and worthwhile. One important aspect of this complementarity is the openness of LC detector trigger. A consideration of the event size and data rate suggest that computing and I/O technology may enable a fully open trigger, for which all relevant detector information is written out for every beam crossing. In some scenarios, such as certain gauge-mediated SUSY and universal extra dimension models which produce signatures containing soft charged tracks and undetectable long-lived heavy particles, this capability could prove essential.

In addition to pushing the frontiers of computing technology, the development of a fully open trigger would require substantial electronics R&D, and perhaps even detector physics R&D, in order to achieve the necessary degree of zero-suppression. Other aspects of proposed LC detector options, such as a finely pixellated TPC endplate, optimized silicon detector readout, and the readout for a highly pixellated energy-flow calorimeter, will also require substantial electronics development work.

## VI. OTHER SYSTEMS

There are a number of other systems, potentially of critical importance to the LC detector and its physics program, whose development will also require substantial R&D and design work.

Far-forward calorimetry, from the limit of the endcap coverage down to within 20 mrad or so of the beam axis, is important for tagging and vetoing forward-scattered beam particles, in order to remove backgrounds to selectron studies and signals with large missing energy, and to detect radiative electrons in studies of two-photon physics. In light of the intense backgrounds associated with the proximity of the beam, these detectors will have to be very robust against radiation damage, and have a high degree of spatial and temporal segmentation. Conventional silicon/tungsten calorimeters may suffice for this region, although their application in the case of the JLC/NLC (for which the inter-train repetition rate is 1.4 nsec) may require the development of fast readout. If backgrounds are particularly high, particularly if detectors are to be mounted below 25 mrad, it may be advantageous to replace the silicon pad detectors with active pixel sensors. The TESLA collaboration, which is considering calorimetry as close as 6 mrad from the beam axis, is also exploring the possibility of using diamond instead of silicon. Finally, the Asian studies have included work on an innovative ‘3D Pixel’ detector[10], being developed at Stanford and the University of Hawaii, which would detect electron-positron pairs from the beam-beam interaction to within 10 mrad of the beam axis. This system would act as a beam profile monitor, with sensitivity to various beam geometry parameters.

The value of dedicated particle identification, somewhere in the region inside the calorimeter, has not been fully explored. None of the baseline designs includes such a device, but the case for its omission remains to be clearly made. In fact, slow, heavy particles are a fairly common signature of theories which extend the Standard Model, suggesting that a time-of-flight system may be worthy of consideration.

The identification of a technology for the muon system has yet to be explored in a comprehensive way. Finally, the task of building large solenoidal magnets with fields of up to 5T will certainly be challenging, and require substantial development effort.

## VII. SUMMARY

The complementarity of the LC program to that of the LHC relies on a number of general factors: the definitive studies enabled by precision tracking and vertexing and the a-priori knowledge of the cms frame and energy, the accurate reconstruction of hadronic final states, and the openness of the LC trigger. All of these would benefit from systems which perform substantially better than their existing counterparts at LEP and the SLC, motivating a vigorous program of research and development. This program needs to include the development and exploitation of sophisticated simulation tools, in order that the hardware development effort be sufficiently informed. This research and development program – both simulation studies and hardware development – should become an important focus for the worldwide particle physics community as the prospects for building a high-energy Linear Collider improve.

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- [1] A wealth of information about the machines, physics, and detectors of the Linear Collider program can be found in the major documents recently provided by the European and North American, and Asian working groups. The TESLA TDR can be found at <http://www.desy.de/lcnodes/tdr/>, the North American Resource Book for Snowmass 2001 can be found at <http://www.slac.stanford.edu/pubs/slacreports/slac-r-570.html>, and the Asian treatise on experimentation at the JLC can be found at <http://acfahep.kek.jp/acfareport/index.html>.
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