Detectors for the International Linear Collider

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Abstract

Some of the challenges of experimentation at the International Linear Collider (ILC) are discussed and the different detector concepts designed to cope with those challenges presented. These different concepts lead to various alternative technologies for the major ILC detector components, some of which are briefly presented.

I. INTRODUCTION

The International Linear Collider (ILC), an electron positron collider with an initial centre-of-mass energy in the range $\sqrt{s} = 200...500\,\mathrm{GeV}$, upgradeable to 1 TeV, is the ideal complement to the Large Hadron Collider (LHC). The clean environment at the ILC will allow precision studies to be made of any new effects discovered at the LHC, as well as making possible the discovery of new physics up to mass scales well beyond the kinematic limit of the machine. A comprehensive and detailed review of the physics potential of the ILC and how this complements that of the LHC is given in [1]. This potential can only be fully realised if the detectors at the ILC's interaction point[1] (IP) have a precision concomitant with the physics requirements. These requirements, and the detector designs and technologies necessary for their realisation, are discussed briefly in this document.

II. DETECTOR REQUIREMENTS AT THE ILC

The demands placed on the ILC detectors are manifold, but can be illustrated by considering a small number of the physical processes which will be studied at the ILC. The first of these is the requirement that it be possible to precisely measure the decay branching ratios of the Higgs boson. Identifying the quarks to which the Higgs decays, primarily the b and c, requires that each of the ILC detectors be equipped with an extremely precise vertex detector (VXD) The inner radius of the VXD is constrained by the ILC backgrounds to be about 15 mm. Flavour identification of high efficiency is necessary as cross-sections at the ILC are small, and of high purity as backgrounds are not negligible. This demands that about 5 hits be recorded on the charged tracks of the b and c hadron decay products with a precision of better than 5 μm. Furthermore, the momentum distribution of the decay products extends down to below 1 GeV, so the beampipe within the VXD and the VXD itself must present the minimum possible amount of material to the particles traversing them.

A further measurement which the ILC detectors must be able to make is the identification of and the determination of the mass of particles such as the Higgs even when these decay invisibly. For example, if the Higgs is produced through the Higgs-strahlung process, $e^+e^- \to Z^0H$, and the Z^0 then decays to a muon pair, knowing the initial e^+ and e^- momenta allows the determination of the Higgs mass provided the momenta of the muons can be measured with sufficient precision. This leads to the requirement that the transverse momentum resolution of the tracking systems of the ILC detectors be $\delta p_T / p_T^2 = 5\times10^{-5}\,\mathrm{GeV}^{-1}$ or better.

If no Higgs boson is found, there will be particular interest in measuring the reactions $e^+e^- \to W^+W^-\nu\bar{\nu}$ and $e^+e^- \to Z^0Z^0\nu\bar{\nu}$, where the W and Z bosons decay primarily to jets of hadrons. Separating the two processes requires that masses of the bosons be reconstructed from these jets with sufficient precision to discriminate between m_W and m_Z, requiring a jet energy resolution of about $\sigma_{jet} = 0.3/\sqrt{E_{jet}\,(\mathrm{GeV})}$. Note that the presence of the neutrinos prohibits the use of simple kinematic constraints in determining these masses. One means of obtaining such energy resolution is to use "particle flow" techniques, i.e. to combine precise measurements of the momentum of the charged particles in a jet made in the tracking system with measurements of the energy of photons made in the electromagnetic calorimeter (Ecal) and of neutral hadrons in the hadronic calorimeter (Hcal), avoiding the loss or double counting of energy. The limiting factor in the jet energy resolution is then not the resolution of the tracking system or calorimeters but the problems associated with correctly identifying how the charged and neutral particles in a jet contribute to the showers measured in the calorimeters. It thus becomes more important to obtain good spatial resolution in the calorimeters than optimal energy resolution. Alternatively, novel calorimetric techniques can be pursued in order to obtain the necessary jet energy resolution using the calorimeter alone.

A further reaction of interest is fermion pair production, particularly given the polarisation of the ILC e^- beam. The left-right asymmetry, A_{LR}, in $b\bar{b}$ or $c\bar{c}$ production is sensitive to the effects of, for example, extra dimensions, allowing such effects to be observed up to masses well above the kinematic limit of the ILC. Interestingly, the coupling constants are such that the effects on lepton production asymmetries are very small. Measuring A_{LR} for b and c quarks requires not only the determination of the flavour of the quarks but also their charge. This places even more stringent requirements on the VXD. All charged particles must be correctly associated with the secondary and, in the case of b

[1] It is likely that the ILC will have only one IP which will be equipped with two detectors. These will share the beam time in so-called "push-pull" operation.

quarks, tertiary vertices if the quark's charge is to be correctly determined.

III. ILC Detector Concepts

Four concepts are currently under discussion for the ILC detectors, the Giant Linear Collider Detector (GLD) [2], the Large Detector Concept (LDC) [3], the Silicon Detector (SiD) [4] and the Fourth Concept (4^{th}) [5]. A common feature of all these detectors is that their ECal and Hcal are placed inside the solenoid which provides the magnetic field for their central tracking systems, ensuring that the amount of energy lost before calorimetric measurements are made is minimised. The first three concepts rely on particle flow techniques to obtain the required jet energy resolution, necessitating the development of calorimeters with good spatial resolution and the associated particle flow algorithms, while the lattermost requires the development of calorimeters which themselves provide excellent jet energy resolution. The relative sizes of the GLD, LDC and SiD are illustrated in Figure 1, which shows the inner radius of the Ecal of these detectors. The 4^{th} detector is of a similar size to the LDC. All the detectors are of the familiar nested design, the inner vertex detector being surrounded by a tracking system, an Ecal, an Hcal the coil providing the central magnetic field and a muon system, as illustrated in Figure 2 for the LDC detector. The flux return for the magnetic field is provided by an iron yoke in the case of the GLD, LDC and SiD concepts, this iron being instrumented to provide muon detection. In the case of the 4^{th} concept, shown in Figure 3, a second solenoid surrounding the first is used to provide the flux return.

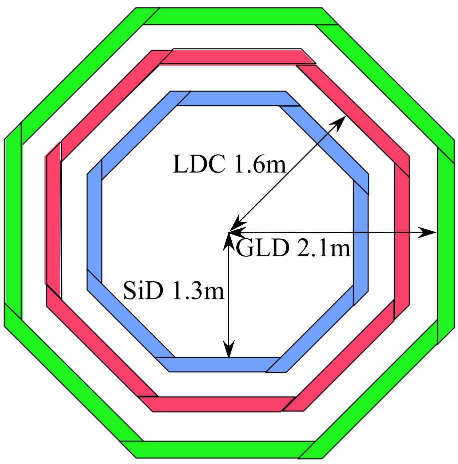

Figure 1 Illustration of relative sizes of GLD, LDC and SiD; shown is the inner radius of the Ecal in each case)

The GLD relies on the large distance particles travel before encountering its calorimeter to separate adjacent energy deposits sufficiently to allow their identification with modest spatial resolution and association with charged tracks where appropriate. The large inner tracking volume also makes possible the use of a relatively small solenoidal magnetic field of 3 T while retaining good momentum resolution. The main elements of the tracking detector are the VXD, a large Time Projection Chamber (TPC) and some supplementary silicon tracking. Surrounding the solenoid is an instrumented iron yoke that provides the flux return for the B field, measures any energy leaking out of the Hcal and measures the paths of penetrating particles such as muons.

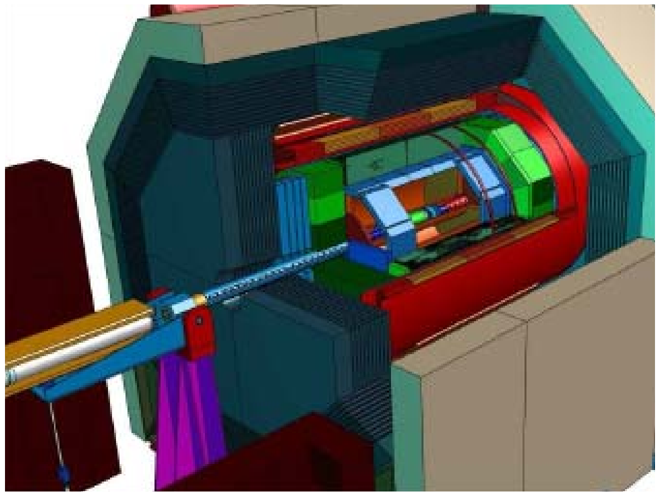

Figure 2 An illustration of the LDC detector.

The LDC is smaller than the GLD, but similar to it in that the tracking volume contains a VXD and a TPC with some supplementary silicon tracking detectors. A stronger magnetic field of 4 T allows the required momentum resolution to be achieved despite the smaller radius of the tracking volume. The smaller size also requires that the spatial resolution of the calorimeters be higher than is necessary for the GLD, but reduces their overall volume. Again, the calorimeters are surrounded by an instrumented iron yoke.

The SiD is the smallest of the detectors being considered for the ILC and utilises a 5 T magnetic field with high precision tracking, provided by a vertex detector and a silicon strip based outer tracking system, to obtain the necessary momentum resolution. Again, high granularity calorimetry is essential for particle flow measurements, and flux return and muon measurements are provided by an instrumented iron yoke.

The 4^{th} detector, shown in Figure 3, represents a departure

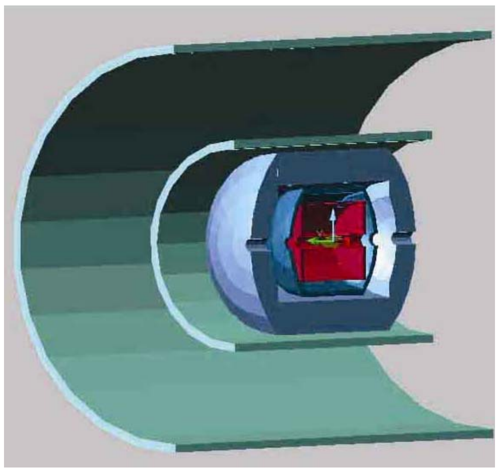

Figure 3 Illustration of the 4^{th} concept, showing the dual solenoid system.

from the above three concepts in several respects. Perhaps most importantly, this detector aims to obtain the required jet energy resolution using high precision calorimetry alone. Further, it utilises two solenoids, the first to provide a magnetic field of about 3.5 T in the central tracking volume, in which the main tracking elements are a VXD and a TPC, possible with some supplementary silicon tracking, and the second to return the flux from the central field in the space outside the Hcal. This obviates the need for an iron yoke, with the associated multiple scattering. The magnetic field in this outer region of about 1.5 T, with direction opposite to that of the field in the inner tracking volume, makes precise muon momentum measurements possible.

IV. Calorimeters for the ILC

Much effort has been invested in research on and development of the calorimeters necessary for precise particle flow measurements. For the relatively small LDC and SiD concepts, extremely good spatial resolution is required, particularly in the Ecal. This means that materials with small Moliere radii must be used and fine granularity readout is essential. The absorber material of choice for the Ecal is thus tungsten, with the readout granularity being matched to the Moliere radius of $R_M \sim 1$ cm. Readout can be provided by silicon pad detectors. The total depth of the calorimeter, which consists of ~ 40 layers, is about 24 X_o or 0.9 λ_0. In order to ensure that the electromagnetic energy deposits remain compact, the thickness of the gaps in the tungsten in which the silicon readout pads are placed must be minimised. There is thus no space for cooling, and readout systems with extremely low power consumption are essential. These are being realised by exploiting the duty cycle of the ILC: bunch trains cross for a period of about 1 ms at the ILC IP and the gap between bunch trains is about 200 ms. A device that effectively exploits this time structure is the Kpix chip [6], which can provide the readout for 1024 calorimeter cells with a power consumption of less than 20 mW. This is achieved by turning off the digital functions of the chip during the bunch train (0.5% of the time) while the analogue signals are amplified and buffered, then turning off the analogue functions during the readout (99.5% of the time). An alternative approach is to use Monolithic Active Pixel sensors (MAPs).

A somewhat lower granularity is required in the Hcal, with current studies suggesting that scintillator tiles of size about 3×3 cm^2 are adequate. These are read out using silicon photomultipliers (SiPMs). Alternatively, "digital" readout could be performed using resistive plate chambers (RPCs) at a granularity of about 1×1 cm^2. This approach records only whether energy above threshold was deposited in the cell, no attempt is made to record the amplitude of the signal.

High spatial resolution electromagnetic and hadronic calorimeters are being studied by the CALICE Collaboration [7]. They have demonstrated that it is possible to track the energy deposited by individual particles in a sufficiently fine-grained calorimeter. Indications are that such calorimeters, and their associated particle flow algorithms, will indeed allow the required jet energy resolution to be achieved, though it is possible that this resolution will fall below $\sigma_{jet} = 0.3/\sqrt{E_{jet}\,(\mathrm{GeV})}$ at the highest jet energies, as the separation between the energy deposits in the calorimeter decreases.

The GLD concept aims to obtain an effective readout granularity of 1×1 cm^2 in its Ecal by using a combination of orthogonal $1 \times 20 \times 0.2$ cm^3 scintillator strips in successive gaps in the absorber material, backed up by scintillator pads of size $4 \times 4 \times 0.2$ cm^3. For all these layers, readout will be via wavelength shifting fibres and SiPMs.

The alternative approach to obtaining the required jet energy resolution being pursued by the 4th concept requires the development of a fine-grained sampling Hcal with multiple fibre readout. Scintillating fibres allow the measurement of all of the charged particles produced in a shower, while the Čerenkov light produced in quartz fibres is sensitive primarily to the highly relativistic electrons in the electromagnetic component of the shower. The binding energy losses in hadronic showers are roughly proportional to the number of neutrons produced and can thus be deduced by detecting these neutrons. This can be done, for example, using fibres doped with lithium or boron. Hence, the three major components that contribute to hadronic showers can be separately measured, allowing precise determination of the total jet energy despite the large fluctuations in the proportions of these components. Dual readout, using quartz and scintillating fibres, has been tested in the DREAM calorimeter [8].

The 4th concept supplements the above Hcal with a crystal Ecal, again with dual quartz and scintillating fibre readout.

V. Tracking Detectors

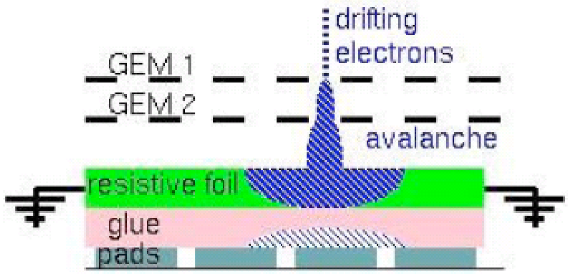

Figure 4 Use of resistive foil to disperse charge across several TPC readout pads following gas amplification using a pair of GEM foils.

As is mentioned above, three of the four detector concepts propose that a large TPC be the main element of their central tracking systems. These have the advantage that they have a large sensitive volume, measure many space points on the paths of charged particles offering excellent pattern recognition capabilities, present only about 3% X_0 to normally incident particles and allow particle identification using dE/dx. However, the momentum resolution required at the ILC exceeds that which has been achieved at e^+e^- detectors using TPCs to date and the TPC end plates represent a significant amount of material, so improvements in the technology are needed. For example, although the baseline design of the LDC concept specifies that the TPC be read out using multi-wire proportional chambers (MWPCs) with pad sizes of about $2 \times 6\ mm^2$, similar to the approach that has been successfully used at other e^+e^- detectors, much interesting research is being pursued on alternative readout systems [9]. Some of these utilise micro-patterned gas detectors such as Gas Electron Multiplier (GEM) foils or Micro-mesh Gas (Micromegas) detectors. The limitations on the resolution when such readout is used often result from the width of the pads on which the signal is induced following gas amplification. Resolution can be improved by dispersing the charge across several pads, hence allowing centroid determination, as is illustrated in Figure 4.

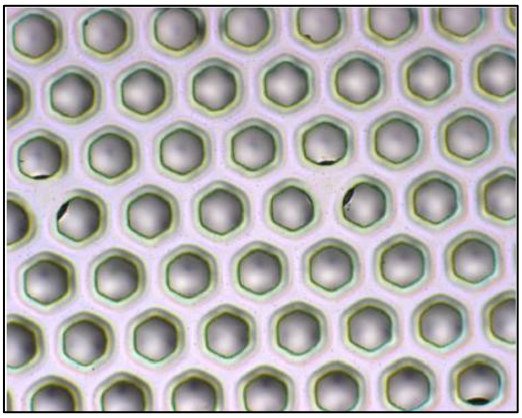

Figure 5 Patterned metal layer used to provide gas gain for TPC readout integrated onto MediPix2 sensor.

An alternative approach to improving the resolution offered by the TPC is to integrate the MPGD on to a pixel sensor by post-processing the sensor wafers. This has been successfully done for MediPix2 sensors [10], which have a pixel size of $55 \times 55\ \mu m^2$. The patterned metal above the chip, shown in Figure 5, allowed gas gains of up to 10^4 to be achieved in an 80:20 $Ar:CO_2$ gas mixture. Problems with occasional sparking, which destroyed the readout, may well be overcome by incorporating a few mm thick highly resistive amorphous silicon layer to protect the sensors.

While the GLD, LDC and 4[th] concepts have chosen to rely on gaseous tracking systems, the SiD requires the increased point precision provided by silicon sensors to obtain a transverse momentum resolution of $\delta p_T / p_T^2 = 5 \times 10^{-5}\ GeV^{-1}$ or better. Efforts here are largely directed at reducing the material budget of silicon strip detectors to values well below those typical for the LHC. This requires the development of low power electronics, as well as light but rigid support structures. The Kpix chips mentioned above in the context of the calorimeter readout represent one possible approach to low power readout and the SiD concept has invested considerable effort in the design and study of low mass support structures for its tracking sensors. The modules, illustrated in Figure 6, are based on carbon fibre and rohacell, with a 50% void, and present a material budget of only 0.8% X_0 per layer to the particles which traverse them. These modules are mounted on a low mass framework, again using carbon fibre technology.

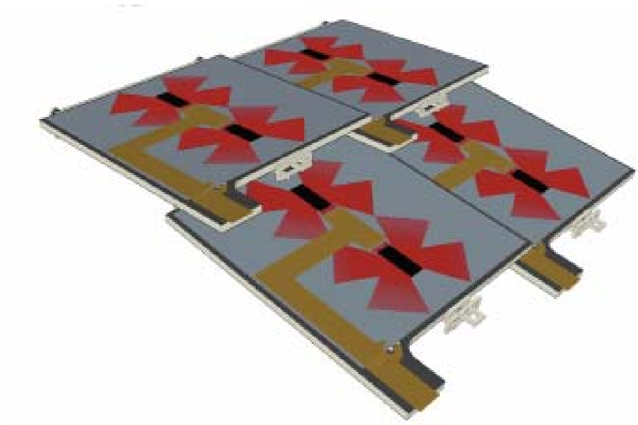

Figure 6 Four modules of the SiD central silicon track detector.

VI. VERTEX DETECTORS

In addition to the physics requirements discussed above, significant constraints are placed on the ILC VXDs by the collider itself. Trains of about 3000 bunches pass through the beampipe within the detector at a frequency of approximately 5 Hz. Within these trains, tightly focused electron and positron bunches collide roughly every 350 nanoseconds generating not only the e^+e^- interactions of interest but also large numbers of electron-positron pairs which cause background hits in the vertex detector. For a detector with pixels of size $20 \times 20\ \mu m^2$, this implies the signals in the sensors must be read out or stored about 20 times during the bunch train, that is, roughly every 50 μs, to ensure that the occupancy remains below about 1%.

A further challenge at the ILC is illustrated by the experience of the SLD vertex detector, the only vertex detector operated in a linear collider environment to date. This detector suffered from beam-induced pickup, presumably from the leakage of RF power generated by the wake fields of passing electron and positron bunches.

The complications of satisfying both theconstraints placed on the VXD by the machine and satisfying the physics requirements have led to the investigation of many sensor types. Not surprisingly, given the success of the VXD3 vertex detector of the SLD [11], Charge-Coupled Devices (CCDs) are one of these. Two CCD architectures are being studied. The first uses $20 \times 20\ \mu m^2$ pixels and achieves high readout speeds by getting rid of the serial register found in conventional CCDs and placing readout circuitry at the bottom of every pixel column. Even with the large increase in readout speed this column parallel architecture offers, the image register must be clocked at a rate of 50 MHz if readout is to be achieved in the required time. Such CCDs have been produced and tested, together with column parallel readout chips which have been bump-bonded to the CCDs. These bump-bonded assemblies have been shown to function well, albeit so far only at reduced clock speeds [12]. CCDs for which the required 50 MHz clock rate should be achievable are currently under test with second generation column parallel readout chips, as are chips designed to produce the 20 A drive signals necessary to clock the charge through the CCDs.

The second CCD architecture that is being considered for the ILC avoids the need for high-speed readout by increasing the number of pixels by a factor of about 20 compared to the above design, hence maintaining a similar occupancy, provided the number of pixels under which charge is collected for each traversing track remains similar. These Fine Pixel

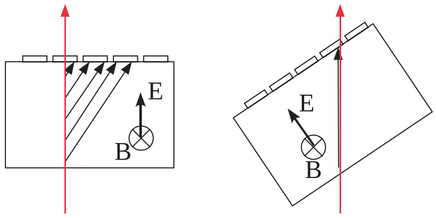

Figure 7 Fine Pixel CCD illustrating the orientation needed to prevent charge spreading due to Lorentz angle effects in detector's B field.

CCDs [13] thus have a pixel size of 5×5 μm^2, are fully depleted to minimise the spread of charge and so oriented that they compensate for the Lorentz angle at which the electrons drift in the CCD due to the detector's magnetic field, as illustrated in Figure 7.

Several groups are working on the design of CMOS Monolithic Active Pixel Sensors (MAPS) for the ILC VXD. For example, the Strasbourg group has reported resolutions as good as 1.5 μm from its 20×20 μm^2 pixel MIMOSA9 sensors [14]. The challenge here is to design full length ladders using this technology, while keeping the material budget as small as possible. In addition to sensors with high speed readout, CMOS devices with a set of capacitors in each pixel have been proposed. These would allow conversion of the charge collected in the pixel to a voltage and storage in pixel during the bunch train, with readout following in the

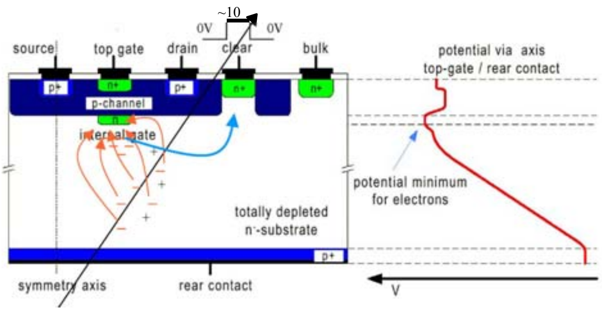

Figure 8 Operation principle of the DEPFET sensor.

inter-bunch train gap at a more relaxed pace. First tests of these devices have been carried out.

A further interesting sensor for the ILC vertex detector is the DEPFET [15], the operating principle of which is illustrated in Figure 8. Progress with designing the electronics necessary to readout and steer this sensor has been good. They promise low noise operation at room temperature and resolutions of 9.5 μm have been obtained from sensors with 20×25 μm^2 pixels.

A novel sensor which also allows storage of the signals in-pixel during the bunch train and later readout is the In-situ Storage Image Sensor (ISIS). Within each imaging pixel, this device has a small storage CCD. The charge collected in the imaging pixel is stored in this CCD and read out during the inter-train gap, a column parallel readout speed of about 1 MHz being adequate. This device promises to provide very high tolerance to electromagnetic interference effects as the signal charge is trapped in the buried channel of the storage CCD during the bunch train and charge to voltage conversion and readout happen in the relatively quiet period between bunch trains. First "proof-of-principle" devices have been tested and functioned well [12]. The integration of CMOS and CCD features onto one wafer represents the major challenge for the further development of this sensor.

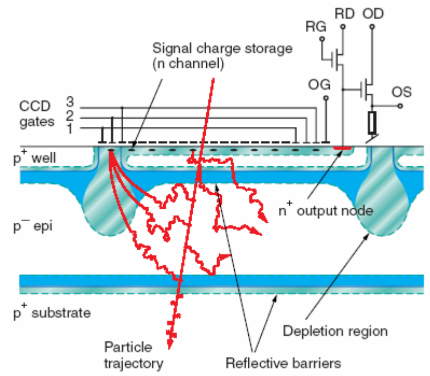

Figure 9 Illustration of the operating principle of the ISIS.

VII. Summary

Physics at the International Linear Collider demands that the ILC detectors provide more precise vertex and track information, as well as better jet energy measurements, than has previously been possible. These demands have spawned interesting developments in calorimetry, tracking, vertex detection and in the interplay between these elements of the ILC detectors. Some of these developments have been briefly described in this report.

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