DETECTOR R&D

T. BEHNKE
DESY, Notkestrasse 85 D-22607 Hamburg, Germany
E-mail: Ties.Behnke@desy.de

The next big project in high energy physics should be a high energy e^+e^- linear collider, operating at energies up to around 1 TeV. A vigorous R&D program has started to prepare the grounds for a detector at such a machine. The amounts of precision data expected at this machine make a novel approach to the reconstruction of events necessary; the particle flow ansatz. This in turn influences significantly the design of a detector for such an experiment. Apart from work ongoing for the linear collider detector, preparations are under way for an update of the LHC. This requires extremely radiation hard detectors. In this paper the state of the different detector development projects is reviewed.

1. Introduction

Over the last few years a consensus has emerged within the particle physics communities worldwide that the next big machine to be built should be an electron-positron linear collider,[1] operating at energies between a few 100 GeV and approximately one TeV. In a series of international workshops the physics community has evaluated both the physics programme to be performed at such a machine, and the resulting requirements for both the machine and the detector at this machine. They have been documented among others in the TESLA technical design report, the SNOWMASS report and the JLC roadmap book.[2−4]

The consensus achieved within the community builds upon a long and very successful history of first developing, then of testing the Standard Model of particle physics at ever more powerful accelerators. Machines like LEP, HERA, the Tevatron, and the B factories have collected impressive data samples and performed precision tests of the Standard Model at energy scales approximately up to the weak scale. Starting in 2007, the Large Hadron Collider, located at CERN, will continue the detailed investigation of the Standard Model and the search for physics beyond the Standard Model. It is hoped that at the LHC the last missing piece in the Standard Model puzzle, the Higgs Boson, will be discovered as well as signs of possible new physics beyond the Standard Model. The LHC will be the first collider which will push the energy scale well beyond the electroweak scale, close to the TeV energy scale.

The LHC by itself however will not be able to fully reveal the physics at these high energy scales. It should be complemented by an electron-positron collider reaching energies of about one TeV. Such a machine will be able to investigate in detail the structure of the electroweak symmetry breaking and study the Higgs Boson, if it exists. In addition nearly all scenarios for physics beyond the Standard Model will have observable signatures in the energy range covered by such a linear collider. Thus such a machine will complement the studies which can be done at the LHC.

Over the last decade tremendous work has been done to develop detectors for the LHC. The LHC exposes detectors to previously unheard-of radiation doses, thus forcing the development of very radiation hard technologies. Upgrades already now planned for the LHC will push the expected doses higher by another order of magnitude, thus requiring another big step in the development of radiation hard detector technologies.

In contrast the experimental conditions at the electron-positron linear collider are relatively benign. The full realization of the physics potential of the machine however implies that a new level of precision in the reconstruction of the complete event should be obtained. Over the last years a fully integrated approach to event reconstruction has been studied in detail, where the individual parts of the detector are optimally combined in the reconstruction to achieve the best possible reconstruction of the underlying event.

In this article the state of the developments of detector technologies and reconstruction strategies for the next generation of colliders is discussed. Particular emphasis is given to the detector at a linear electron-positron collider, but work ongoing in the preparation of the upgrade of the LHC is also discussed. While an impressive amount of detector

R&D has been done and is still being done for the first generation of detectors at the LHC this is not the subject of this review.

2. Event Reconstruction at a Lepton Collider

The physics programme anticipated for the planned linear electron-positron collider demands large amounts of data collected over a wide range of center-of-mass energies reaching from 90 GeV at the Z^0 resonance, to close to 1 TeV, at the maximum energy such a machine can reach. The type of measurements which the detector has to be capable of performing ranges from the reconstruction of individual particles in the final state, over the reconstruction of event properties as e.g. the jet structure in multi-jet events, to the precision measurements of vertices in heavy flavor decays.

A typical process to be studied at this machine is the decay of a light Higgs boson. If a light Higgs particle exists, the reconstruction of its properties, including the coupling to different types of final-state particles, requires a data sample approaching several ab^{-1}. For Higgs boson masses below approx. 140 GeV bottom quarks in the final state play an important role, at higher masses, complicated multi-jet final state dominate. The same is true for Standard Model processes, as e.g. top decays, which again result in multi-jet final states. The reconstruction of the Higgs mass or the properties of these particles requires, that these jets are measured superbly, thus stressing the capability of the detector to reconstruct the jet parameters.

A typical list of requirements for a detector at a linear electron-positron collider can be summarized in the following list.

- The detector should have an excellent capability to reconstruct the overall event. The method currently favoured is the so-called Particle Flow Technique, which will be discussed in more detail below.[5,6] Since particle flow is based on the optimal combination of tracking and calorimeter information this implies:
  - excellent track reconstruction capability. The detector should be able to find and reconstruct tracks from charged particles with close to 100% efficiency over a large solid angle. A benchmark condition is that the momentum resolution should be such that the mass resolution achieved for the recoiling muons in the reaction $HZ \rightarrow H\mu^+\mu^-$ is not dominated by detector effects.[7]
  - excellent reconstruction of charged and neutral particles in the calorimeter. The separation of neutral and charged particles is particularly important, thus stressing the spatial resolution of the calorimeter. To maximize the separation between charged and neutral particles a strong central magnetic field is necessary.
  - excellent hermeticity of the detector, to be able to fully reconstruct the event. In addition the sensitivity to many new physics signals is greatly enhanced in a hermetic detector.
- Many properties of the event can be reconstructed if the flavor of the final state is known. For heavy flavors this can be done with excellent efficiency and purity if lifetime information is available for the decaying particles. A supreme vertex detector therefore is needed, to reconstruct long-lived particles with excellent resolution.[8]

Over the years a number of different detector concepts have been studied in some detail. Two different approaches have emerged, a so-called large and a small detector type. Both have in common an excellent electromagnetic and hadronic calorimeter, arranged inside a central solenoidal magnetic field. They differ in the strategy of the tracking system. The large detector relies on a combination of a high resolution vertex detector, typically a pixel device, with a large volume gas-based drift detector, typically a TPC. The small detector on the other hand uses only Si based detectors for the tracking. The high resolution vertex detector is the core detector for both vertexing and for track finding, and is supplemented by a small number of Si-detector layers on the outside, to add momentum measurement capabilities and to bridge the gap between the vertex and the calorimetric detector.

2.1. *The Particle Flow Concept*

The concept of particle flow, sometimes also called energy flow, has been used in a number of detectors throughout the last decade. Particle flow works best at moderate energies of the individual particles, below about 100 GeV. In this regime the tracker is much superior in momentum resolution to a calorimeter for charged particles, and thus charged particles are primarily measured with the tracking system. Neutral particles on the other hand are reconstructed in the calorimeter. The particle flow algorithm then is the optimal combination of the information from the two detector systems, to achieve the best overall reconstruction possible.

Although this concept found wide spread acceptance already during the running of LEP, none of the detectors at LEP or at any other large collider were designed from the beginning with the concept of particle flow as one of the main requirements.

The goal of a particle flow reconstruction can be summarized very simply: reconstruct the four-vectors of all particles which participate in the event. This goal is typically achievable for charged particles, but much more difficult for neutral particles. In the past the reconstruction of neutral particles was often limited to the reconstruction of the energy carried by all - or a subset of - neutral particles, rather than the individual reconstruction of neutral particles. The reconstruction of photons buried in jets e.g. is nearly impossible with a typical LEP detector. This is one of the explanations why a detector at e.g. LEP[9] can reconstruct the energy of jets only with something like $60\%/\sqrt{E}$.

Monte Carlo studies show that an ideal reconstruction algorithm,[6] which finds each particle and measures its energy, its direction and its momentum correctly, could reach a jet energy resolution of $14\%/\sqrt{E}$.

The importance of excellent jet energy resolution is demonstrated quite clearly in the reconstruction of WW or ZZ final states. These are important signatures both for Standard Model and for new physics signals, and a clear separation between WW and ZZ final states is very important. With a jet energy resolution of $60\%/\sqrt{E}$ a separation of both final states is nearly impossible with good purity and efficiency. At about $30\%/\sqrt{E}$ the two signals are much more clearly separated. The different behaviour is shown in Fig. 1. Over the years a resolution of $30\%/\sqrt{E}$ has come to be accepted as a good compromise between the theoretically possible and the practically achievable resolution.

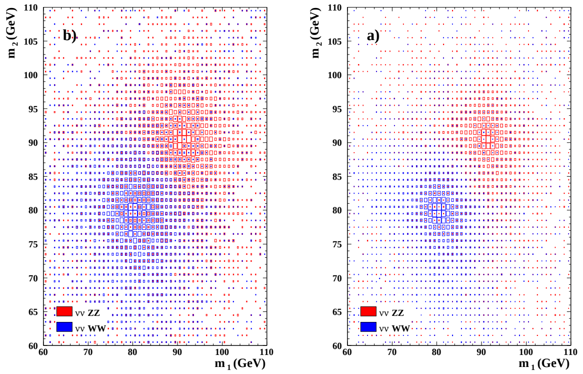

Figure 1. Reconstructed mass for hadronic WW and ZZ final states, as reconstructed[2] for an energy resolution of (left) $60\%/\sqrt{E}$, (right) $30\%/\sqrt{E}$.

3. Detector Developments for the Linear Collider Detector

The requirements listed in the previous detector have been realised in a number of different detector concepts. A side view of a particular detector, the proposal for the TESLA collider published in the TESLA TDR[2] is shown in Fig. 2. In this section the different subsections of the proposed detectors, and the technological challenges are discussed.

3.1. *Vertex Detector*

The detector closest to the interaction point is the vertex detector, constructed from Si pixel detectors. It has to meet very stringent requirements on the resolution, achieve excellent stand-alone pattern recognition, and ensure a robust and reliable operation in this environment prone to significant background induced from the beams.

A number of different technologies are under discussion for this detector. All have in common that they are based on pixel detectors, with pixels not larger than around $50 \times 50\ \mu\text{m}^2$. This is to ensure that the occupancy of these devices during operation stays below a few percent. Most hits seen in this detector will be background induced, primarily from beam-beam generated backgrounds. In addition the devices are exposed to a fairly large -

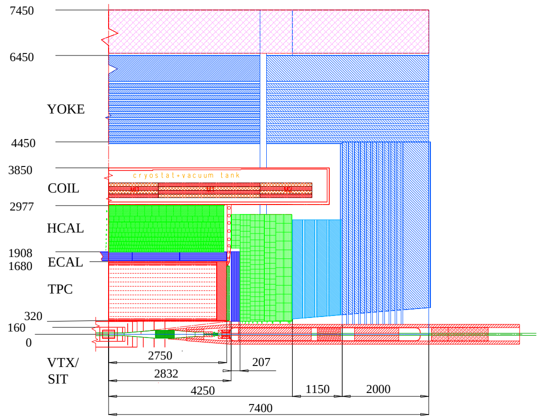

Figure 2. Sideview of one quadrant of the proposed TESLA detector.

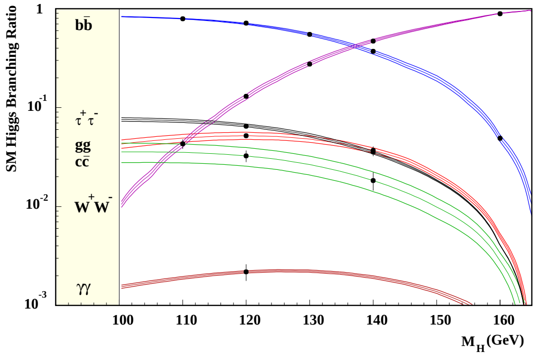

Figure 3. Predicted and reconstructed[10] branching ratio, using the simulation, of the Higgs boson into different fermion species.

though small by LHC standards - flux of neutrons of up to 10^{10} $n\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, coming from the interaction of the beam and its halo with the beam elements close to the interaction point. Technologies which are under investigation are based on CCD sensors, CMOS sensors, DEPFET sensors, and some other newer technologies. Although initial studies were also performed for the use of LHC-type pixel detectors at such a machine, they are not vigorously pursued since these detectors are much thicker than the other technologies under discussion.

The requirements on the vertex detector are defined primarily through the need for excellent tagging of secondary vertices. At SLD the power of a CCD type pixel detector has been convincingly demonstrated, resulting in outstanding efficiency and purity for the tagging of bottom hadrons. At the linear collider this capability is extended, by reducing the size of the pixels, and reducing the inner radius of the first layer, to improve significantly on the tagging of charmed hadrons. The possible performance of such a device is demonstrated in Fig. 3. Here the predicted and reconstructed branching ratios of a light Higgs boson are shown, for different final states. Even the decays into charm or tau final states can be clearly reconstructed.[10]

3.1.1. *CCD vertex detectors*

The CCD technology is a mature technology. Its applicability in a collider experiment has been demonstrated at the SLD experiment, where a detector with some 400 million channels was installed. Compared to that installation a detector at a linear collider has to be read out much faster. At the same time the material present in the detector should be reduced as much as possible, to minimize the multiple scattering of long lived particles in the detector and thus increasing the precision which which its lifetime can be reconstructed. For a recent review see the References.[11]

Since the colliding electron and positron bunches in a linear collider are arranged in long trains, with bunch distances of at most a few hundred ns, a CCD detector can not be read out in between bunches. The signals will be integrated over many bunch crossings. To minimize this number the readout speed has to be increased as much as possible. At the moment a 50 MHz clock is foreseen, an increase over the SLD system of nearly a factor of 10. To further speed up the readout a column-parallel readout is planned, where rather than reading out the complete chip serially into one line, each column of pixels is read out into one independent readout chip. Recent results indicate that such performance can indeed be achieved in prototype chips.

Another area of intense R&D for CCD detectors is the thickness of the devices. Since the active part of the CCD is concentrated in a rather thin layer of Si on one side of the chip, it naturally lends itself to thinning of the detector. The influence of the thickness of the detector on the determination of the impact parameter is shown in Fig. 4.

3.1.2. *CMOS detector technology*

Over the last few years the CMOS technology has been intensely studied in view of their applicability to vertex detectors. In a CMOS based vertex detector

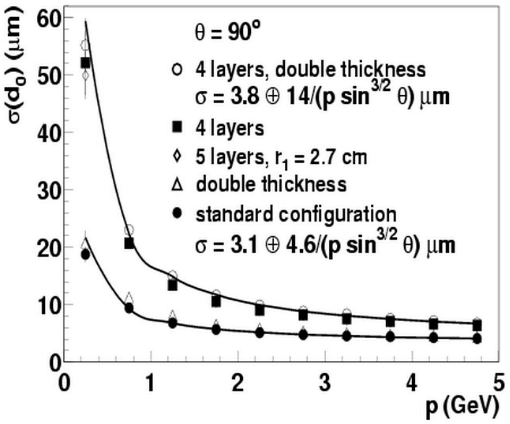

Figure 4. Impact parameter distribution for a four and a three layer vertex detector, and for different material distributions.[8]

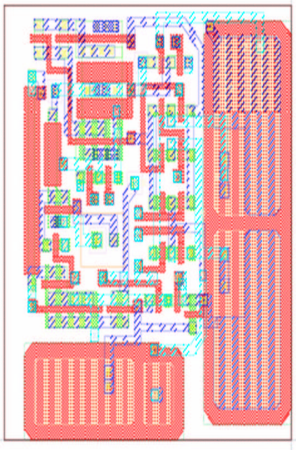

Figure 5. Enlarged view of one pixel of the MAPS silicon detector.

the charge produced under a pixel is not transported to the edge of the chip, as it is done in a CCD, but is processed by electronics integrated into the pixel. These types of detectors are known as MAPS (Monolithic Active Pixel Sensor) devices.[12] A view of the masks of a single pixel is shown in Fig. 5. After processing the signal is stored in the pixel until it is read out by some electronics located on the edges of the device.

Compared to a CCD detector a MAPS is operationally simpler. Since no charge needs to be transported over long distances it is expected to be more radiation hard. However very little experience exists about the use of such devices as particle detectors. Prototype chips have been operated very successfully during the last years. However there are still a number of open technical questions, which will be addressed over the next few years. As for the CCD the question of the material present in the sensors needs to be settled. While the potential for thinning of the devices is similar to the one for the CCD, no actual tests have been performed so far. For the use of a detector in the confined space close to the beampipe, the power consumption of the devices is going to be very important. As each pixel is an active device, potentially more power will be dissipated along the active area of the detector than is the case for the CCD.

A number of groups have formed over the last few years which design, produce and test prototype structures. Recently the sixth generation of test chips were produced and have been tested with beam. The planned vigorous R&D program over the next few years should result in enough information to decide whether these devices are an alternative to a CCD-based detector.

3.1.3. *Other technologies*

A number of other technologies are under investigation at present. The DEPFET pixel detector again places active elements into the pixel. The charge created in a depleted region of the Si wafer is drifted into a potential well, where it is stored. It is then read out with a transistor integrated into the chip. Multiple readout is possible. Since the amount of electronics integrated into one pixel is very small, power consumption per pixel is very low. As for the other options, readout speed and thinning of the sensors are areas where development work is needed.[13]

A number of variants of the CMOS technology exist. In the FAPS scheme the limited readout speed of the MAPS chip is addressed by implanting more than one storage capacitor into one pixel, thus allowing the storage of more than one signal on one chip, which are then read out serially.

3.1.4. *Comparison of the different technologies*

At the moment no conclusion can be reached as to which of the different technologies will in the end be chosen. All are under active development, and all face challenges to meet the requirements for use at a linear collider detector. Of particular importance is the readout speed, which directly determines how many bunch crossings are integrated into one readout cycle. Thinning of the detectors is another active area of research, where no final answers exist for any of the technologies. For use in a real detector the real-estate needed for the final detector system - that is the active area and the inactive area needed for readout - is another important criterion. A vigorous research program has started at different laboratories around the world to try and answer these questions.

3.2. *Tracking Detectors*

The two different detector options being studied differ primarily in their choice of technology for a main tracker: gaseous detector versus Si detectors. Depending on the choice the role the tracking detector will play is slightly different.

In the case of a large volume gaseous detector, as e.g. proposed for the TESLA detector, the tracker will be one of the main devices used in track finding and track reconstruction. This will ease the expectations for the vertex detector for track finding together with the hope of making the whole system more robust against backgrounds and tracking inefficiencies.

In the model of a "small" detector the tracking is done by a combination of the vertex detector and a few layers of Si strip detectors. The main part of the tracking is left to the vertex detector. The Si strip detectors are primarily used to measure the momentum of tracks in the strong magnetic field, by adding enough lever-arm to the small vertex detector. This detector concept is based on the excellent experience at the SLD detector, where the high granularity CCD vertex detector has proven itself to be a very robust and powerful tracking device.

3.2.1. *The TPC tracker*

A TPC has been used in a number of large scale experiments as the central tracking device. For the linear collider a TPC has been proposed because it offers a large number of space points with good single hit spatial resolution (around 100 μm seems achievable), and reasonable double track resolution.[2] This concept has been shown to result in a tracking system with high track finding efficiency. The large number of points reconstructed in the TPC makes for a very robust system, with a lot of build-in redundancy. In addition a gas detector offers the capability to identify different particle types via dE/dx, the specific energy loss. In Fig. 6 a side view of a proposed TPC is shown.

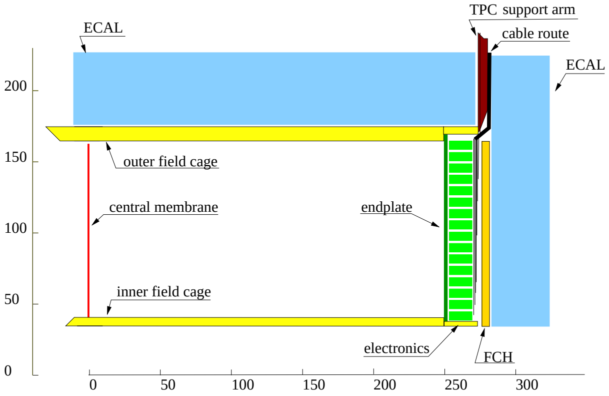

Figure 6. One quarter view of a TPC as proposed for a detector at a linear collider.

A major area of development is the readout technology. Traditionally wire chambers have been used to detect the charge produced in the TPC volume. Wire chambers are a proven technology, resulting in a robust system. There are however a number of disadvantages connected to a wire chamber readout. First of all, the wires require a sophisticated mechanical structure to support their tension. This introduces material in an area in front of the endcap calorimeter, where the amount of material should be minimized. Wire chambers are in addition limited to a minimum spacing between the readout elements, the wires, which is in the region of mm. This implies intrinsically different granularities in the directions along or perpendicular to the wire. This results in a reduced resolution and increased systematic errors.

Recently micro-gas detectors have received a lot of attention. Different types of such detectors are GEM (Gas Electron Multiplier) or micromegas.[14,15] A GEM consists of a insulating foil, typically Kapton, clad on both sides with a thin layer of copper. Holes are present in the foil and the copper connecting both sides. If a potential difference is applied to the two copper surfaces, a strong electric field develops in the holes. If such a foil is placed perpendicular to the drift direction of the electrons, and if proper potentials are applied so that the electrons are forced into the holes, gas amplification takes place inside the holes. The charge after amplification is extracted from the hole on the opposite side, and detected by pads connected to charge sensitive amplifiers. Micromegas operate on a similar principle, except that the GEM foil is replaced by a metallic grid, placed on top of the pad plane at a short distance. The gas amplification takes place in the area between the grid and the pad plane.

Micro-gas detectors are investigated as possible replacements of the wire chambers in a TPC. In this case a system of MPGDs is placed at the end of the drift volume, charge amplification takes place in these devices, and the charges are detected on pad planes as they are in more conventional wire chamber TPC. The main advantages of a MPGD TPC is that the readout is mechanically more simple, and might result in a device with less material than the conventional chamber. In addition these devices are intrinsic two-dimensional, and should introduce smaller systematic errors than the wire TPC.

During the last few years an international group has formed with the goal of investigating and developing the technology of a TPC equipped with micro pattern gas detectors.[16] The group includes members mostly from Europe and the Americas, with links to Asian groups forming. Several prototype TPCs have been built, equipped with GEMs or with Micromegas. The principle of the operation has been demonstrated, and resolutions have been studied. Recently for the first time small prototype chambers were exposed to large magnetic fields as they are expected in a real detector. While results are still very preliminary, no adverse effects of these magnetic fields on the operation of the MPGD or the TPC were found. As an example the measured ion feedback in a prototype TPC is shown in Fig. 7, as a function of the magnetic field. The behavior of the feedback on the field is not very strong, and very smooth. Although no quantitative model exists at the moment to explain the observed behavior, qualitatively is does not present any surprises.

The developments of TPCs are not limited to the area of detector development for the linear collider. In fact TPCs are used in a wide area of different applications. An interesting new device under construction is the TPC to be used in the ICARUS experiment in Gran Sasso.[18] Here the drift volume is filled with liquid Argon, resulting in extremely long drift times of up to 1 ms for the 1.5 m drift distance.

3.2.2. *The all-Si tracker*

The alternative tracker option is based on a few layers of Si strip detectors arranged in cylinders and disks to fill the space between the vertex tracker and the calorimeter.[19] Based on studies done for the LHC experiments it is expected that the excellent resolution obtainable with these devices compensates for the fact that there are only a few points, thus maintaining a good tracking efficiency. In the existing designs particular emphasis is placed on good reconstruction in the plane perpendicular to the beam, measuring primarily the curvature of the tracks in the magnetic field. For cost reasons only one or two of the layers are instrumented to measure both the $r-\phi$ and the z coordinate.

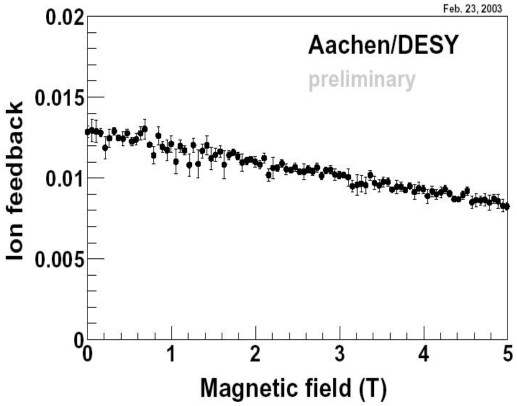

Figure 7. Ion feedback measured in a TPC prototype chamber, as a function of the applied magnetic field.[17]

The main challenges of this design are the mechanical design of a large area Si strip detector system, minimizing the material present in the support structures, and at the same time optimizing the stability of the device.

While the tracking and the measurement of the parameters of isolated tracks can be done in such a detector as well as in a TPC based tracker, it is not yet known, whether such a tracker influences the particle flow reconstruction in any way. The detection of long lived particles and the tagging of photon conversions are two topics, which will be studied in great detail in the near future, and which will help to understand the relative merits of the different detector concepts.

3.3. *The Electromagnetic Calorimeter*

In the framework of a particle flow reconstruction algorithm the ideal calorimeter would provide a three-dimensional picture of the shower developing inside the detector. This ideal detector can be approxi-

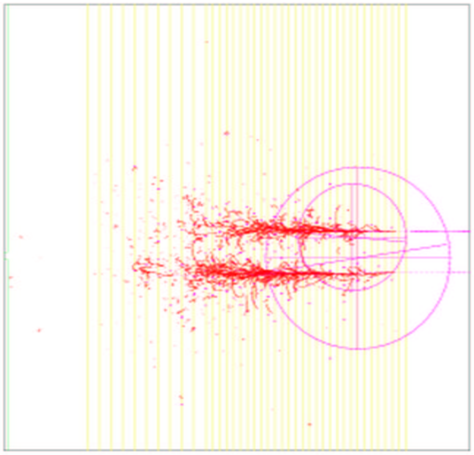

Figure 8. Signals deposited by two closeby photons in the Si-W sampling calorimeter.[6] The distance between the two photons is approximately 1 cm.

mated by a sampling calorimeter with the typical size of a cell given by approximately the Molière radius in the material. If this is supplemented by many samples along the direction in which the shower develops, a detailed reconstruction of individual showers becomes possible. The reconstruction of close-by charged and neutral particles is helped by the immersion of the device in a strong magnetic field, separating charged and neutral particles. The size of the device and the resolution obtainable are given primarily by the size of the Molière radius. A tungsten sampling calorimeter therefore is an attractive option.[2] In Fig. 8, the resolution with which two photons from a conversion would be seen, is illustrated.

The Molière radius in a W-based calorimeter is around 1 cm, depending on the thickness of the sensitive detector. Most studies at the moment consider a Si detector as the most promising option for such a device. Si detectors are thin, can be easily subdivided into small cells, and can be produced to cover large areas. The main problem is the cost - a Si based electromagnetic calorimeter will be rather expensive, and becomes a major cost factor for a linear collider detector.

The current R&D activities concentrate on finding a technological solution for building a large area readout plane from Si, with low enough noise and fast enough readout to be a viable option. At the moment it is thought that a 2.5 mm thick readout gap is necessary between Tungsten plates. However developments are under way to reduce this to close to 1.5 mm. The typical cell sizes which are considered are between 5×5 mm^2 and 10×10 mm^2. In Europe an option is being investigated where a second readout board on top of the Si detector will pick up the signals from the individual cell, and route them to the edge of each calorimeter module. In the US the modules are divided into "wafers" of approximately 8″ diameter, with a readout chip located centrally on the chip. In either case the transfer of the charge to the readout over a fairly long distance presents a significant challenge.

The CALICE collaboration, which has members from Europe, the Americas and Asia, plans to build a small scale prototype of such a detector by the end of 2004. This detector will then be extensively studied in a series of test beam experiments, together with a HCAL prototype, described below.[20]

3.4. *The Hadronic Calorimeter*

In a calorimeter optimized for the particle flow reconstruction the hadronic calorimeter plays an important role as well. Ideally this device is built as a tracking calorimeter as well, which allows the detailed reconstruction of the development of the hadronic shower. Compared to the electromagnetic calorimeter, the reconstruction of a hadronic shower is in some respect more challenging, since the presence of neutrons in the shower result in a much less localized nature of the shower, and thus in more problems identifying the components of a shower. In addition a good hadronic calorimeter not only should be able to reconstruct the hadronic part of the shower, but should also be sensitive to the always present electromagnetic component in each hadronic shower.

At the moment two different concepts for such a calorimeter are being discussed. The more conventional approach uses a sampling calorimeter with e.g. a scintillator based readout to record the position and the size of the energy deposits.[20] A different approach concentrates fully on the spatial information by reading out the calorimeter in an extremely finely grained way, but only recording whether or not a cell has been hit. This so called digital approach can work, because a strong correlation exists between the total energy deposited in the calorimeter, and the number of cells hit.[20] This is demonstrated in Fig. 9. Shown is the result of a simulation study correlat-

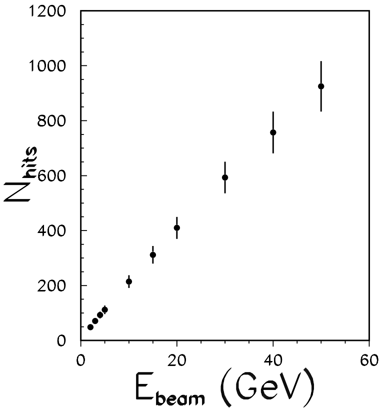

Figure 9. Correlation between the number of cells with hits, and the total energy in the calorimeter, for a hadronic calorimeter.

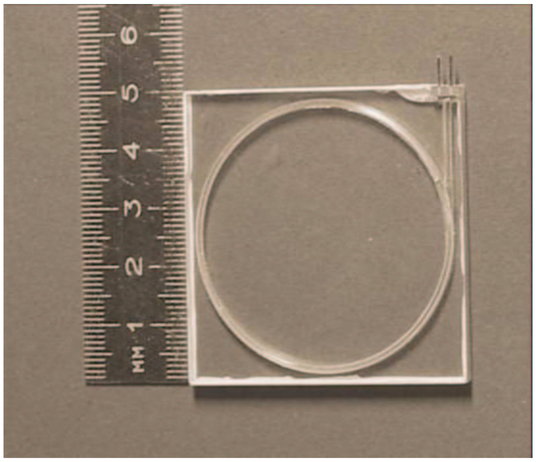

Figure 10. Photograph of a single 5 × 5 cm^2 scintillator tile equipped with a SiPM. The SiPM is visible at the top right corner of the tile.

ing the number of hits seen with the total energy deposited.

The first conventional calorimeter option will most likely be realised as a sampling calorimeter with scintillator readout. Even here the particle flow concept requires that the granularity is very good, so that the hadronic components of the shower can be resolved, and that the electromagnetic components can be correctly attributed to the correct shower. Typical cell sizes considered are around 5 × 5 cm^2. The readout of a correspondingly large number of tiles presents a significant challenge. Conventional photo-tubes are disfavored because of cost, and because they do not operate in strong magnetic fields. Long clear fibers would need to be routed outside the central coil, into a low field region, with the corresponding significant complication and cost. A novel approach is being investigated whereby Si-based miniaturized photo-multipliers are integrated directly into the tile. Such devices, which became recently available from a Russian group, offer something like 1000 pixels in a 1 mm^2 area. Each pixel by itself can not record analog information. However the number of pixels which register a photon is a measure of the total amount of light, and thus these devices can be used in an analog readout scheme. Recent tests have confirmed that the integration into the tile is possible, and that a reliable measurement of the amplitude is possible. These devices would significantly simplify the problem of reading the large number of cells. A sample tile with the SiPM integrated is shown in Fig. 10.

The digital HCAL option requires a readout system which can record energy deposits in cells of typically 1 × 1 cm^2 over large areas. Si detectors are much too expensive for such things. Alternative solutions based on Resistive Plate Chambers (RPC's) or on GEM based systems are under investigation. Given that the rate requirements for a detector at a linear collider are not very high, it is expected that resistive plate chambers should be adequate for this device.

An equally big challenge to the development of the necessary hardware for such a tracking calorimeter is the development of reconstruction algorithms to exploit the potential of these devices. Conventional calorimeter reconstruction methods are no longer adequate for the large granularity in a particle flow detector. Novel approaches are needed, which in many way resemble pattern reconstruction algorithms developed for tracking systems. This work is still in its infancy, but its fast development is essential should the particle flow calorimeter become a realistic option. They are needed to both gauge the performance of these devices, and understand beam test data, and are essential in designing and in optimizing the detector in terms of cell size, absorber thickness etc.. An important goal of the first generation of test beam experiments planned for 2004/ 2005 therefore will be the verification of simulation tools, so that reliable predictions for the performance of the complete system can be made.

4. Detector Developments for the SLHC

For a possible upgrade of the LHC collider, radiation hardness of the detector components will be an even greater challenge than it is already for the LHC. It is expected that at the SLHC (Super-LHC) the 1 MeV equivalence dose of neutrons at a distance of 4 cm from the beam line will increase from an expected $\Phi(R = 4\ \text{cm}) = 3 \times 10^{15}\ \text{cm}^{-2}$ to $\Phi(R = 4\ \text{cm}) = 1.6 \times 10^{16}\ \text{cm}^{-2}$ - a rate which none of the known detector technologies will be able to tolerate.

A number of groups have started a R&D activity with the goal of significantly improving the radiation hardness of Si based detectors. A systematic program has started, based upon the work done for the first stage of the LHC experiments, to explore the mechanism responsible for radiation damage, and to find ways to increase the radiation hardness. Recently significant progress has been reported when using epitaxial Si detectors grown on Czochralski substrates. Oxygenated silicon has for some time been known to improve the radiation hardness of Si - in particular with respect to photon irradiation. The new epitaxial detectors seem, in addition, to show a significantly improved radiation hardness under hadronic irradiation. From preliminary results shown by the group it appears that for a hadronic fluence of a few times $10^{16}\ \text{cm}^{-2}$ the charge collection efficiency drops by approximately 40%. For the first time a material has been demonstrated which is still functional after exposure to the full SLHC dose.[21]

5. Summary

The next generation of experiments in High Energy Physics, most notably at the electron-positron linear collider, pose many challenges to the detector developer. In particular the concept of a detector optimized for particle flow requires a significantly more powerful calorimeter, with up-to-now unheard of segmentation. Such a device together with high resolution tracking devices are the subject of an intense and international R&D effort.

Significant progress has been made in the past years in the radiation hardness of Si detectors. This is of particular importance for a possible LHC upgrade project.

In summary detector R&D is a very active and interesting field, where many new results are to be expected over the next few years. When in a few years a decision on the linear collider is expected enough detector R&D should have been done to make a rational decision for a detector at such a machine.

6. Acknowledgments

I wish to thank many colleagues from the different linear collider physics and detector R&D groups around the world, who contributed material for this review, and were available for questions and discussions. I wish to thank the organizers of this conference for a productive and pleasant conference.

References

1. P. Grannis, S. Komamiya, T. Matsui and F.Richard (eds.), *Understanding Matter, Energy, Space and Time: The case for the* e^+e^- *linear collider*, see http://sbhep1.physics.sunysb.edu/˜grannis/ wwlc_report.html.
2. F. Richard, J.R. Schneider, D. Trines and A. Wagner (eds.), *TESLA: Technical Design report, DESY 2001-01, ECFA 2001-209, TESLA Report 2001-023, TESLA-FEL 2001-05* (2001).
3. American Linear Collider Working Group, *Linear Collider Physics, BNL-52627, CLNS 01/1729, FERMILAB-Pub-01/058-E, LBNL-47813, SLAC-R-570, UCRL-ID-143810-DR, LC-REV-2001-074-US* (2001).
4. Asian Comittee for Future Accelerators, Japan High Energy Physics Committee, High Energy Accelerator Research Organisation, *GLC Project* (2003).
5. H. Videau and J.C. Brient, *A Si-W calorimeter for linear collider physics*, prepared for 10th International Conference on Calorimetry in High Energy Physics (CALOR 2002), Pasadena, California, 25-30 Mar 2002.
6. V. Morgunov, *Calorimetry design with energy-flow concept (imaging detector for high-energy physics)*, prepared for 10th International Conference on Calorimetry in High Energy Physics (CALOR 2002), Pasadena, California, 25- 30 Mar 2002.
7. J. Hauschildt, *LC note LC-DET-2001-036* (2001), see http://www-flc.desy.de/lcnotes.
8. S.M. Xella-Hansen *et al.*, *LC-DET-2003-061* (2003), see http://www-flc.desy.de/lcnotes.
9. M. N. Minard, *Jet energy measurement with the ALEPH detector at LEP2*, prepared for 10th International Conference on Calorimetry in High Energy Physics (CALOR 2002), Pasadena, California, 25-30 Mar 2002.
10. M. Battaglia and K. Desch,*hep-ph/0101165* (2001).

11. C. Damerell and K. Stefanov, *LC-DET-2003-060* (2003), see http://www-flc.desy.de/lcnotes.
12. M. Winter, *New developments for silicon detectors* prepared for 31st International Conference on High Energy Physics (ICHEP 2002), Amsterdam, The Netherlands, 24-31 Jul 2002.
13. P.Fisher *et al.*, *LC-DET-2001-004* (2001), see http://www-flc.desy.de/lcnotes.
14. R. Bouclier *et al.*, *The gas electron multiplier (GEM)*, *IEEE Trans. Nucl. Sci.*} **44**, *646 (1997).*
15. Y. Giomataris, P. Rebourgeard, J. P. Robert and G. Charpak, *Nucl. Instrum. Meth. A* **376**, 29 (1996).
16. The LC TPC group, LC-DET-2002-008, see http://www-flc.desy.de/lcnotes.
17. P. Wienemann, DESY, private communication.
18. F. Arneodo *et al.*, *Nucl. Phys. Proc. Suppl.* **54B**, 95 (1997).
19. C. J. Damerell *et al.*, *Ideas for the NLC detector*, *SLAC-REPRINT-1996-009* (1996).
20. S. Valkar *et al.*, *A Calorimeter for the e+ e- Tesla Detector: Proposal for R&D*, *DESY-PRC-RD-01-02* (2001).
21. G. Kramberger *et al.*, report to be published.

DISCUSSION

David Miller (University College London): It's a comment on an early graph where you showed the WW and ZZ separation, and it is just a plea that people must not think that WW and ZZ are the background at the linear collider. WW and ZZ are where we find out what is going on in electroweak symmetry breaking. It's a signal.

Ulrich Goerlach (Univ. of Strasbourg): You mentioned very briefly the MAPS detectors. Although you didn't explain in detail their functioning, I was a little bit surprised about your statement that they may lead to a larger material budget. I do not agree with this. Since MAPS use only a very small part of the silicon as an active medium, they have the potential to be thinned down to a few tens of a micron, leading to very thin detectors, and thus to a very low material budget.

Ties Behnke: The point is, that as in most of these detector technologies, it is not known how far we can push the thinning of these different detectors. In fact, even for the CCD technology, where people thought for a while, they understood how to do the thinning, problems turned up when they actually tried to build a test device. I think it is just one of the very important points which needs to be addressed by a vigorous R&D program. We just have to see at the end what comes out, and how well these different technologies perform.

Paula Collins (CERN): I just have a comment and a question. The comment is that for Czochralski silicon we have recently tested irradiated Czochralski silicon with fast electronics in a test beam and the results will be coming out very shortly. The question is then: a year ago in the linear collider community there was the concept floating around of using silicon drift detectors for the TPC. I'd like to know if this is still something which is favored? As I understood the time stamp is very useful for sorting out the integration of many events in the CCD detector, and that was the advantage of it.

Ties Behnke: To be honest, I am not aware of any vigorous program in that direction. The standard TPC does give you enough timing information to separate bunches at least at TESLA, where you have some 300 ns or so time. From this point of view a potentially better timing resolution is not needed. For the warm machines, where the timing between bunches is much shorter, a separation of individual events from each pulse will be very hard in any technology under discussion, and probably is not needed.

Alan Sill (Texas Tech University): Now I have built detectors, tracking detectors for many years. I love tracking detectors, so don't get the sense of this question wrong. But I think you have really repeated a lot of the statements that have been made for many years about linear collider detectors that really need to be challenged. For example the idea that you get resolution by counting all the little particles. And you see where this leads you. You are driven toward very complex detectors, very expensive ones, especially calorimeters. A sweep the table argument, that's much simpler, is to say let's get the energy resolution in the calorimeter. Let's build a high-precision calorimeter that gets a lot of energy resolution. In that 60% of the charged particles are of course a lot of hadrons. Is there any attempt in the linear collider community to challenge some of these statements that have been made for many years, but maybe need to be challenged a little bit?

Ties Behnke: There is a lot of activity trying to really find out whether the statements that I made are stringent or not. It has been established using simulations that the particle flow algorithm applied to a detector with granularities as I described, can give you the resolution we want for the jet energy - I showed the example of WW and ZZ separation. The resolution which has been achieved in existing detectors is about a factor of two worse. Exactly how far one can push the conventional approach, or how much one can simplify the detectors I discussed, and still achieve decent resolution, is not really known. The trouble is that these questions are not easily answered. You really have to go through the complete reconstruction procedure if you want to study whether such a system does or does not work. You have to develop reconstruction programs both for the tracker and for the calorimeter. You have to really do a proper job in simulating and reconstructing the events, which just takes time. These efforts are ongoing. There aren't complete results yet. But, yes, people do look quite critically whether you really need this tremendous granularity in the calorimeter, with the correspondingly large cost, or if you can get away with a much simpler device.