The Vertex Tracker at Future $e^+e^-$ Linear Colliders

M. Battaglia
University of California, Berkeley CA, USA and
CERN, CH-1211 Geneva 23, Switzerland

Abstract

The physics program of high energy $e^+e^-$ linear colliders relies on the accurate identification of fermions to study in detail the profile of the Higgs boson, search for new particles and later probe the multi-TeV mass region by direct searches and precision electro-weak measurements. This paper reviews the requirements, conceptual design and sensor R&D for the Vertex Tracker.

Key words: vertex detector; linear collider

1. Introduction

The LHC collider at CERN represents the next step in the study of the high energy frontier in particle physics. We expect that the data collected in $pp$ collisions will provide evidence of the Higgs bosons and of Supersymmetry, or of other New Physics signals. The Higgs bosons observation will be a decisive breakthrough in our understanding of the origin of mass and electro-weak symmetry breaking. Signals of New Physics will clarify the solution to the hierarchy problem of the Standard Model. But neither the precision study of the Higgs profile nor the investigation of New Physics will be completed at the LHC. There are measurements which will be limited in accuracy, while others may not be feasible at all.

A high energy, high luminosity linear collider (LC), able to deliver $e^+e^-$ collisions at center-of-mass energies $\sqrt{s} = 0.3$-$0.5$ TeV with luminosity in excess to $10^{34}$ cm$^{-2}$s$^{-1}$, later upgradeable to about 1 TeV, is considered as the next large scale project in accelerator particle physics. Present projects focus on warm RF (mostly X-band as for the NLC and JLC projects) or super-conducting cavities (proposed by the TESLA collaboration) to achieve the needed gradients $\Gamma_2$. Beyond it, multi-TeV collisions appear to be achievable at a linear collider, using a novel two-beam acceleration scheme at high frequency, developed in the CLIC study $\Gamma_3$.

The Vertex Tracker is expected to provide the jet flavor identification capabilities and the accurate event reconstruction that make the linear collider unique and allow its physics program.

If the Higgs boson exists and it is light, as the present data indicates, its couplings to fermions of different flavor, and hence of different mass, must be accurately measured as a fundamental proof of the Higgs mechanism of mass generation, as well as its self-coupling. Efficient flavor tagging in multi-jet events and determination of heavy quark charge will be instrumental to study signals of New Physics both through the direct production...
of new heavy particles, coupled predominantly to \( b \) and \( t \) quarks, and by precise electro-weak data at the high energy frontier. Physics requirements push the vertex tracker specifications to new levels. While much has been learned in two decades of R&D on Si detectors for the LHC experiments, the LC motivates today new and complementary directions. Its experimental environment, with its lower event rate and radiation flux, admits Si sensors that are substantially thinner, more precise and more segmented than at the LHC. Technologies which have not been applicable in the high radiation environment of proton colliders are also available, as well as sensors of new concept. But significant R&D is required. CCD vertex detectors have already demonstrated very high resolution and segmentation with low multiple scattering at SLD\(^3\). But for the CCD technology to be applicable to the LC improved radiation hardness and a factor 100-1000 increase in readout speed are required. Technologies successfully developed for the LHC program, such as hybrid pixel sensors, are sufficiently radiation hard and can be read out rapidly. But they now need to be developed into much thinner devices with smaller cell size to improve their position resolution. Finally new technologies, such as MAPS, SOI and DEPFET sensors, are emerging as other potentially attractive solutions. But they need to be demonstrated on large scales and be tailored to the LC applications. These developments need to be guided by a continued program of physics studies and detailed simulations to define the optimal design and technology choices.

Several Vertex Tracker designs have been proposed, relying on different sensor technologies. They all share the use of pixel devices, due to the high particle density which disallows the use of microstrip detectors. Emphasis is placed on minimizing the material budget, to improve track extrapolation performances also at small momenta in multi-jet final states.

2. Experimental Conditions

The Vertex Tracker at the LC will be exposed to background and radiation levels and to track densities unprecedented for \( e^+e^- \) collider machines, though still lower compared to proton colliders. The main source of background in the interaction region is due to \( e^+e^- \) pairs produced and bent in the intense electro-magnetic interaction of the colliding beams. Such pairs set the most stringent constraint on the Vertex Tracker geometry. The radius and maximum length of the innermost sensitive layer are defined by the envelope of the deflected pairs. The radial and longitudinal position of the point of crossing of the pair envelope can be approximated as function of the number of particles in a bunch, \( N \), the solenoidal magnetic field, \( B \), and the bunch length, \( \sigma_z \) by:

\[
R[cm] = 0.35 \sqrt{\frac{N}{10^{10}}} \frac{1}{B[Tesla]} \frac{z[cm]}{\sigma_z[mm]} \frac{1}{10^{10}} (1)
\]

\[
z[cm] = 8.3 R^2 B[Tesla] \sigma_z[mm] 10^{10} N. (2)
\]

Warm RF technology requires \( \sigma_z \) to be small, while the field strength \( B \) is limited by the optic and quadrupole requirements at the final focus. The inward bound on the detector radius is thus set at \( \simeq 1.5 \) cm, up to 1 TeV. This radius appears safe also for the collimation of synchrotron radiation. At a multi-TeV collider the innermost radius must be pushed to \( \simeq 3 \) cm.

Particle tracks in highly collimated jets also significantly contribute to the local track density in physics events. This is expected to be 0.2-1.0 hits mm\(^{-2}\) at 500 GeV, to reach 0.5-2.5 hits mm\(^{-2}\) at 3.0 TeV. These figures are comparable to, or even exceed, those expected at the LHC: 0.03 hits mm\(^{-2}\) for proton collisions in ATLAS and 0.9 hits mm\(^{-2}\) for heavy ion collisions in ALICE. The dose due to charged particles is expected to be manageable: \( \simeq 50 \) krad y\(^{-1}\). On the contrary, the neutron background may be important for the sensor technology choice. Neutrons are produced in electromagnetic interactions of the spent beams and radiated particles. The resulting
3. Vertex Tracker Conceptual Design

The Vertex Tracker will likely consist of a multi-layered barrel section, directly surrounding the beam-pipe, complemented by forward disks to ensure tracking down to small angles. Five layers should ensure standalone pattern recognition and tracking capabilities as well as redundancy.

The strongest requirements on the impact parameter resolution are set by the need of efficiently disentangling $H^0 \rightarrow b \bar{b}$ from $H^0 \rightarrow c \bar{c}$ Higgs boson decays. This can be best done by exploiting the difference in invariant mass and multiplicity of the decay products. But for this method to be efficient, secondary particle tracks need to be identified by their significantly large impact parameter down to low momenta. The charm jet tagging efficiency degrades by a factor 1.5-2.0, at constant purity, if the impact parameter resolution $\sigma_{ip}$ changes from $5 \mu m \pm 5 \mu m/p_t$ to $10 \mu m \pm 30 \mu m/p_t$. Since jets are tagged in pairs, such loss corresponds to 2 to 4 times the equivalent data statistics. Several other physics processes support these requirements. A multi-layered vertex tracker with the first sensitive layer at 1.5 cm from the interaction region and 1% $X_0$ of total thickness can provide the target $\sigma_{ip} = 5 \mu m \pm 5 \mu m/p_t$. Single point resolution of 5 $\mu m$, or better, has been achieved with different techniques.

The main challenge comes from the limit on the material budget. Several solutions are being studied ranging from 20 $\mu m$ thick CCD ladders (0.06% $X_0$/layer) supported only at their ends to back-thinned hybrid pixel sensors (0.3% $X_0$/layer). Extracting the heat dissipated by the sensors and their electronics is another important issue in the engineering design of the vertex tracker and the material budget may be driven by the power dissipation. The typical value is of order of 15 $\mu W$/pixel for CCDs, 40 $\mu W$/channel for HPS and $4 \mu W$/pixel for MAPS. The total power for CCD sensors may be lowered to about 10 W if 1 V clocks are feasible. The additional dissipation from the driver and read-out electronics is less critical being confined outside the sensitive part of the detector. In addition CCDs may need to operate at low temperature to improve their radiation tolerance. The heat management may also depend on the bunch structure of the collider and will need to be studied in details. In particular pulsed power operation is being considered to profit of the collider low duty cycle and tests have started.

Finally suppression of noise and RF pick-up is essential, due to the large number of channels.

4. Si Sensor Technology and R&D

4.1. Charge Coupled Devices

CCD sensors have characteristics which match in principle the main LC performance requirements. Their pixel size is small, giving single point resolution better than 4 $\mu m$, and the sensors are thin, $\approx 20 \mu m$. Two main limitations remain: the read-out timing and the neutron radiation damage. At a collider with the TESLA bunch structure, the $\approx 3$ M pixels in the first layer, need to be read-out in not more than 50 $\mu s$ to ensure a background hit density below 5 mm$^{-2}$. Therefore a read-out clock of about 50 MHz is necessary. A novel column parallel read-out (CPCCD) scheme is being developed by the LCFI Collaboration. Prototypes have been designed and produced and are presently being tested, which operate with low-voltage clock amplitudes to reduce power dissipation. The most important radiation damage in CCDs is bulk Si displacements caused by heavy particles causing charge carrier trapping. Deep level bound states have lifetime longer than the inter-pixel transfer time and the charge is lost resulting in a drop of the charge transfer efficiency (CTE). This becomes particularly important since charges need to be transported over lengths of order of cm. Two possible techniques to improve
the CTE are being studied: cooling the detector to increase the trapping lifetime and keep the trapping centers filled and filling traps with light pulse flushing to avoid further charge loss. Tests have been performed and indicate that the signal loss can be lowered with light pulses. First results give a signal loss reduction from 29% to 18% after integrating $6.5 \times 10^8$ $n \text{ cm}^{-2}$ and can be improved with an optimised setup.

4.2. Hybrid Pixel Sensors

Hybrid pixel sensors (HPS) have provided a reliable solution to 3D tracking from LEP 2 to LHC. Their main limitations, due to the total sensor plus chip thickness and the limited single point resolution, may be overcome with a dedicated R&D program. Beside the vertex tracker, HPS detectors offer a suitable technology also for forward tracking with good resolution and fast time-stamping. A scheme with interleaved nodes, extending that usefully applied to microstrip detectors, was proposed to improve the point accuracy by interpolating the charge sharing on neighboring read-out nodes. Test structures have been produced and successfully tested, providing a proof of principle. A single point resolution of $\simeq 3 \mu m$ can be achieved, if tracks are sufficiently isolated. Now a dedicated R&D program on back-thinning and bump-bonding represents the main focus, to reduce the detector thickness.

4.3. MAPS Sensors

Monolithic Active Pixel Sensors (MAPS) exploit the epitaxial layer of the CMOS wafer as detector substrate, to integrate the detector and the front-end readout electronics on the same silicon wafer, using standard VLSI CMOS technology. The development of MAPS detectors started with application as photon detectors where they are becoming increasingly popular. Their application to detection of m.i.p. signals was initiated as a LC R&D and the first vertex tracker based on this technology is under construction for the STAR detector upgrade at RHIC. The signal is collected from the undepleted bulk or epitaxial layer where the charge carriers spread by thermal diffusion. Small pixel size and integrated electronics offer a good solution to the problems of resolution and layer thickness. Detector have been tested on particle beams and after irradiation. Tolerance to neutron fluxes has been established up to $10^{12} \text{ n/cm}^2$, which is well beyond the LC requirements. A full scale 1 M pixel sensors has proved that MAPS offer full efficient detectors with 2 $\mu m$ accuracy and excellent two-track resolution. New developments are addressing the readout speed and providing increased functionality, including data sparsification and integrated correlated double sampling. Test structures in 0.35 $\mu m$ technology with 5 MHz column parallel readout are being evaluated.

4.4. Other Options

The variety of technologies for applications at the linear collider is further enriched by new concepts currently being investigated.

Another route toward monolithic sensors is the realization of FET devices integrated in high-resistivity fully depleted $n$ bulk, which amplify the charge at the point of collection, avoiding losses. This scheme, adopted by DEPFET devices, provides full bulk sensitivity and the low input capacitance ensures low noise and have robust correlated double sampling capabilities. DEPFET sensors have been developed primarily for X-ray imaging. A dedicated R&D for the LC vertex tracker has started.

Another attractive architecture for a monolithic pixel sensor is Silicon on insulator (SOI), where a Si film sits on a thin insulator over a high resistivity Si substrate acting as detecting volume. The readout is built in the thin layer. There are a number of technological issues to be addressed in matching the pixel manufacturing technique with the CMOS processing. SOI test structures have been fabricated 0.8 AMS technology and characterized. Recently signals from ionizing particles have been recorded, providing a first proof of principle of this design.

Emerging ion etching technologies have enabled the development of a new 3D detector scheme.
In these detectors small diameter holes are drilled through the silicon wafer. Carriers drift perpendicular to the wafer thickness and normal to the particle trajectory. 3D sensors are characterized by good radiation tolerance and very fast time response, owing to their geometry. This makes them interesting for applications at small radius in the forward region.

In a farther future, the deposition of hydrogenated amorphous Si layer on ASIC may also become a competitive technology, bringing advantages both in terms of fast signals and, possibly, productions costs [10].

5. Conclusions

An active and diversified R&D program on Si sensors for LC applications is presently ongoing world-wide. It addresses issues which are complementary to the developments tailored to the LHC, while other aspects of detector engineering, services and read-out electronics will largely profits from the LHC experience. At present several detector architectures appear promising. However, it will be important to extend the R&D phase, until the time of project approval and final detector design. As pixel sensors have a wide, interdisciplinary field of applications, ranging from structural biology to medical imaging and astrophysics, the linear collider R&D effort is also significantly nested to those broader developments.

References
[1] G. Loew, Nucl. Phys. Proc. Suppl. 117 (2003) 385.
[2] A 3 TeV $e^+e^-$ Linear Collider Based on CLIC Technology, G. Guignard (editor), CERN-2000-008.
[3] K. Abe et al., Nucl. Instrum. Meth. A 400 (1997) 287.
[4] G. Wagner, LC-DET-2001-048
[5] Physics at the CLIC multi-TeV Collider, M. Battaglia, A. De Roeck, J. Ellis, D. Schulte (editors), to appear as CERN Report.
[6] M. Battaglia and K. Desch, in AIP Conf. Proc. 578 (2001) 163 [arXiv:hep-ph/0101165].
[7] K.D. Stefanov, Nucl. Instrum. Meth. A 501 (2003) 245.
[8] J.E. Brau and N. Sinev, IEEE Trans. Nucl. Sci. 47 (2000) 1898.
[9] M. Battaglia et al., IEEE Trans. Nucl. Sci. 48 (2001) 992 [arXiv:hep-ex/0101020].
[10] G. Claus et al., Nucl. Instrum. Meth. A 465 (2000) 120.
[11] R. Turchetta et al., Nucl. Instrum. Meth. A 501 (2003) 251.
[12] H.S. Matis et al., IEEE Trans. Nucl. Sci. 50 (2003) 1020 [arXiv:nucl-ex/0212019].
[13] M. Amati et al., Nucl. Instrum. Meth. A 511 (2003) 265.
[14] R.H. Richter et al., Nucl. Instrum. Meth. A 511 (2003) 250.
[15] S.I. Parker, C.J. Kenney and J. Segal, in Proc.of the 28th Int. Conf. on High-energy Physics, World Scientific, 1997, vol. 2, 1743.
[16] P. Jarron, A. Shah, N. Wyrsch, to appear on Nucl. Instrum. Meth. A.