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Vertex tracking at a future linear collider

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ABSTRACT

The anticipated physics program at an high energy e^+e^- linear collider places special emphasis on the accuracy in extrapolating charged particle tracks to their production vertex to tag heavy quarks and leptons. This paper reviews physics motivations and performance requirements, sensor R&D directions and current results of the studies for a vertex tracker at a future linear collider.

1. Introduction

A high energy e^+e^- linear collider has emerged as possibly the most practical and realistic way towards collisions of elementary particles at constituent energies matching those of the LHC with high luminosity. The ILC project is based on the use of superconducting RF cavities providing gradients of $\simeq 30$ MV/m to produce collisions at centre-of-mass energies $\sqrt{s}$ = 0.25–1 TeV [1]. In order to achieve multi-TeV e^+e^- collisions, the CLIC project develops a new acceleration scheme where a low-energy, high-current drive beam is used to accelerate the main beam through high-frequency transfer structures, which have achieved gradients in excess of 100 MV/m [2].

Heavy flavours represent an essential signature of the anticipated physics of interest. The study of the Higgs sector of the Standard Model, of TeV-scale new physics and the search for new phenomena at very high mass scale through electro-weak precision observables, all depend on the identification and decay reconstruction of t, b and c quarks and of τ leptons [3]. This physics program requires a vertex tracker able to extrapolate the particle tracks back to their production vertex with high accuracy over a broad momentum range. The linear collider requirements have motivated a vigorous and diversified R&D program which has seen monolithic pixels of various technologies emerging as a mature and well-performing option for vertex tracking applications.

2. Tracking accuracy, flavour tagging and experimental conditions

The standard figure of merit for tracking accuracy is the resolution on the impact parameter, σ_{IP}, defined as the distance of closest approach of the particle track to the colliding beam position. This can be parametrised as

$$\sigma_{IP} = a \oplus \frac{b}{p\sin^k\theta} \quad (1)$$

where θ is the track polar angle and $k = 3/2$ for the R–Φ and 5/2 for the z projection. The target parameters for a 0.25–0.5 TeV collider are $a = 5$ μm and $b = 10$ μm GeV^{-1}.

The identification of hadronic jets originating from heavy quarks is best achieved by a topological reconstruction of the displaced secondary and tertiary vertex structure and the kinematics associated to B hadron decays. The ability to reconstruct the sequence of primary, secondary and tertiary vertices depends on the impact parameter resolution. Jet flavour tagging for the linear collider extends the strategy successfully adopted in SLD, to date the collider experiments with the best track extrapolation accuracy [4]. The ZVTOP algorithm [5], originally developed for physics at SLC and now adapted for use at a linear collider, demonstrated high b-tagging efficiency on fully simulated and reconstructed events [6]. The impact of a change of the a and b parameters in (1) on the physics performance have been studied on detailed simulation and reconstruction. In 500 GeV energy b-jets, doubling the values of a and b from 3 μm and 18 μm GeV^{-1} to 6 μm and 36 μm GeV^{-1}, respectively, results in a 15% decrease of both the number of vertices reconstructed in the B decay chain and the fraction of particle tracks correctly assigned to their vertex of origin. The efficiency for the identification of b jets at a constant purity of 0.90, in a sample where light, c and b flavours are uniformly represented, drops from 0.75 for $a = 5$ μm and $b = 10$ μm GeV^{-1} to 0.25 for $a = 12$ μm and $b = 70$ μm GeV^{-1}. That for tagging c-jets at a purity of 0.70 drops from 0.50 for $a = 5$ μm and $b = 10$ μm GeV^{-1} to 0.29 for $a = 11$ μm and $b = 15$ μm GeV^{-1} [7]. Propagating these effects to the statistical accuracy of physics measurements, such as Higgs decay branching fractions, generally shows that a degradation of a factor of two on the a or b terms of (1) corresponds to a 20–30% equivalent luminosity loss at 0.5 TeV [8,9].

Multiple t and b quarks are expected to be a distinctive feature in several processes in multi-TeV e^+e^- collisions. The signal

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cross-sections are typically of $\mathcal{O}(1\ \text{fb})$ with signal-to-background ratios of 10^{-2}–10^{-5} and two to six heavy flavour jets. The energy of b jets ranges from 50 GeV up to the full beam energy of ~ 1.5 TeV. In the benchmark process $e^+e^- \to H^0A^0 \to b\bar{b}b\bar{b}$, with M_A around 1 TeV at $\sqrt{s} = 3$ TeV, jets have B hadrons flying on average 27 mm and approximately one third of them decays at a radius larger than 30 mm. In addition, forward b-tagging is crucial to study some specific SM processes, which may only be accessible to a multi-TeV e^+e^- collider, such as the triple Higgs coupling, through $e^+e^- \to \nu_e\bar{\nu}_e h^0\ h^0$, and the fermionic coupling of an intermediate-mass Higgs boson, through $e^+e^- \to \nu_e\bar{\nu}_e h^0 \to \nu_e\bar{\nu}_e b\bar{b}$. In this case, the B hadron energy is in the range $25 < E < 300$ GeV, due to the large energy taken by the neutrinos.

The track extrapolation requirements outlined above can be met with a vertex tracker which has thin layers, first measurement close to the beam interaction point and excellent single point resolution. Considering a traditional barrel geometry with two layers located at radii R_{in} and R_{out}, the asymptotic impact parameter resolution a is given by

$$a = \sqrt{(n+1)^2 + n^2}\sigma_{point} \tag{2}$$

where $n = R_{in}/(R_{out} - R_{in})$ and σ_{point} is the single point resolution. With $R_{in} =$ 15–30 mm and a lever arm $R_{out} - R_{in}$ of 30–40 mm, the requirement $a \le 5\ \mu$m implies a point resolution $\sigma_{point} \le 3.5\ \mu$m. The requirement on the pixel pitch, P, comes from the point resolution ($\sigma_{point} \le P/\sqrt{12}$ for binary readout and $\propto P/(S/N)$ for analog readout with charge interpolation) but also from the two-track separation ($\propto P$) and from the occupancy ($\propto P^2$). Single point resolutions equal to, or better than, that required for the linear collider have been obtained in several monolithic pixel technologies, including CMOS MAPS [10], DEPFET [11] and SOI [12], for pixel pitches in the range 10–30 μm and S/N values of 20–130. In particular, CMOS sensors with binary output have demonstrated a detection efficiency $> 99\%$, fake rate $< 10^{-4}$ and point resolution of 3.5 μm, below the $P/\sqrt{12}$ limit of their pixel pitch of 18.4 μm [10,13].

The multiple scattering term, b, is given by

$$b = \sum_i R_i^2 \theta_{0,i}^2 \tag{3}$$

where the index i runs over the material surfaces traversed by the particles and θ_0 is the multiple scattering angle for normal incidence tracks. It is desirable to install the first layer as close as possible to the interaction point to minimise the multiple scattering effect and optimise the asymptotic resolution. In practice this radius is set by the density of low momentum pair electrons and positrons.

Pairs are produced by beam particles scattering on real and virtual photons created in the intense beam–beam electromagnetic interactions. The intrinsic p_t of most of these electrons is small but they get deflected in the electric field of the incoming beam and can reach the detector. Incoherent pairs, spiralling in the solenoidal magnetic field of the detector, form an envelope, whose radius at a given position z along the beam axis defines a lower bound on the position of the innermost detector layer. This bound scales approximately as

$$R \sim \sqrt{\frac{N}{10^{10}}\frac{1}{\sigma_z}\frac{1}{B}z}. \tag{4}$$

N is the number of particles in a bunch ($= 2 \times 10^{10}$ for ILC and 3.7×10^9 for CLIC), σ_z is the bunch length ($= 300\ \mu$m for ILC and 40 μm for CLIC) and B the solenoidal field ($= 3$–5 T depending on the detector concept design) [14,15]. Outside the deflected pair envelope there is a residual pair population, due to large p_t electrons and to particles deflected at large angles or back-scattered from the inner face of the low angle calorimeter, which is located downstream from the interaction point. The ILC has a predicted hit density from incoherent pairs of 4.4 hits $\text{mm}^{-2}\ \text{BX}^{-1}$ at a radius of 16 mm and $\sqrt{s} = 0.5$ TeV, which increases by approximately a factor of two by doubling the beam energy or changing the beam parameters to achieve a constant luminosity. At $\sqrt{s} = 3$ TeV, CLIC has $\simeq 2.2$ hits $\text{mm}^{-2}\ \text{BX}^{-1}$ at a radius of 31 mm [16]. The factor two increase in the radius of the vertex tracker innermost layer at CLIC compared to the ILC results in a change of the multiple scattering term from 10 to 21 μm GeV^{-1}. Pairs are also responsible for an ionising dose of ~ 100 krad/year to be added to a non-ionising dose corresponding to $\simeq 7 \times 10^{10}\ n_{eq}\ \text{cm}^{-2}\ \text{year}^{-1}$ from pairs, which is larger than that due to neutrons, estimated to $\simeq 10^{10}$ neutrons $\text{cm}^{-2}\ \text{year}^{-1}$ at 0.5 TeV [17]. These figures are expected to be comparable, ~ 100 krad/year and $5 \times 10^{10}\ \text{n cm}^{-2}\ \text{year}^{-1}$, for CLIC at 3 TeV [18].

Experience in tracking and vertexing with prototype monolithic pixel sensors has already been obtained by several groups. In particular, the EUDET project and the DEPFET group have extensive experience with tracking beam particles. The EUDET telescope consists of two arms each equipped with three layers of 50 μm–thin CMOS MAPS chips with in-pixel correlated double sampling, column parallel readout with discriminator and zero suppression logic at the end of the column. It provides a track extrapolation accuracy of 1–2 μm on the detector under test. Using a readout time of 100 μs it can operate with large track density, up to 10^6 particles $\text{cm}^{-2}\ \text{s}^{-1}$ [19]. The T966 beam test experiment also operated a beam telescope made of 50 μm–thick CMOS pixel sensors [20]. Four sensors were arranged with a 15 mm spacing which is close to that proposed for the ladders of a Vertex Tracker at the linear collider. It studied the tracking extrapolation accuracy for 1.5 GeV electrons at the LBNL Advanced Light Source (ALS) and 120 GeV protons at the Fermilab Test Beam Facility. With a point resolution of 2.3 μm, the accuracy for extrapolating the reconstructed particle track by 15 mm upstream was measured to be (8.5 ± 0.4) μm and (4.2 ± 0.3) μm at 1.5 and 120 GeV, respectively, which matches the linear collider requirements. In addition, the vertexing accuracy was studied for p interactions in a thin Cu target located 32 mm upstream from the first sensor, corresponding to the distance between the first vertex layer and the interaction point foreseen at CLIC. The longitudinal vertex position resolution of 260 μm for an average track multiplicity of 2.74 closely matches that expected for CLIC of 220 μm for reconstructed secondary decays vertices of B hadrons having an average track multiplicity of 3.02.

3. Low-mass ladders for the vertex tracker

Despite the large design collision energies, charged particles are typically produced with moderate energies, due to the large jet multiplicity or missing energy. b jets are discriminated from c jets based on the number and invariant mass of the secondary particles. This requires most, if not all, of the b charged decay products to be identified. Excellent track extrapolation at low momenta is therefore essential. At 0.5 TeV the c tagging efficiency, at constant purity, in the study of $h^0 \to c\bar{c}$, drops by 25% when changing the ladder thickness from 0.1% X_0 to 0.3% X_0 [21]. The multiple scattering term b plays even a more crucial role than the asymptotic resolution a, in particular for processes which are forward peaked. The fraction of charged B decay products identified as secondaries based on their impact parameter significance, IP/σ_{IP}, in $e^+e^- \to \nu_e\bar{\nu}_e h^0 \to \nu_e\bar{\nu}_e b\bar{b}$ events at $\sqrt{s} = 3$ TeV, drops from 0.85 for $b = 15\ \mu\text{m GeV}^{-1}$ to 0.74 for 35 μm GeV^{-1}. For comparison, it changes by just 2% for $1.5 < a < 3.5\ \mu$m.

Chips of various technologies have been successfully thinned to ≤ 100 μm. Assuming that the sensors are mounted on an 100 μm–thick carbon fiber composite (CFC) ladder, there is little benefit for the multiple scattering term from pushing their thickness below ~ 50 μm. It has been shown that CMOS chips can be