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Vertex Detectors and the Linear Collider

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We review the physics requirements for the ILC vertex detectors, which lead to the specification of silicon pixel sensors arranged as nested barrels, possibly augmented by endcap detectors for enhanced coverage of small polar angles. We describe how the detector requirements are a natural outgrowth of 25 years dvelopment of CCD-based vertex detectors in fixed-target and colliding beam experiments, culminating in the 307 Mpixel SLD vertex detector. We discuss how the technology has recently branched out into about a dozen architectures which might be made to work at the ILC, where the main challenge is to increase the effective readout rate by about a factor 1000 compared to conventional CCDs, while preserving the small pixels (~20 μm) and low power dissipation. Preserving gaseous cooling as at SLD opens the door to layer thicknesses as low as 0.1% X_0. Finally, we consider how best to manage electromagnetic interference associated with the beam wakefields and other RF sources during the bunch train. In conclusion, we suggest a strategy for moving on from the present rich R&D programmes to optimal detectors for the startup of the ILC physics programme.

1. INTRODUCTION

The first fully international discussion of vertex detectors for the TeV-scale International Linear Collider took place at LCWS 1991 in Saariselka, Finland. European studies had previously been limited to physics processes accessible to LEP-quality vertex detectors using silicon microstrip sensors. While these could provide respectable *b*-tagging, their impact parameter resolution [1] fell short of what was even then being achieved at SLD. Encouraged by the performance of the SLD vertex detector using silicon pixel sensors (in the form of CCDs), physicists working at SLC were advocating a more ambitious detector specification with much greater physics potential. Being pixel-based, such detectors would also be far more robust as regards backgrounds. There was by no means a consensus at that first workshop, partly because the SLD vertex detector had not yet demonstrated its physics potential. Fortunately, some influential people became convinced, and Bjorn Wiik, in his brilliant summary talk, commented that 'You're going to need a very good vertex detector'. By the time of the second LCWS in Hawaii in 1993, it was possible to demonstrate [2] that the hit densities of particles in jets, as well as the background rates, precluded the use of microstrip detectors at small radius, so silicon pixels became the preferred technology, and this has remained true ever since. However, the required detector performance has continued to be somewhat contentious, with some physicists clinging to the opinion that only *b*-tagging is seriously needed. One of the purposes of this paper is to summarise the arguments in favour of a much higher performance vertex detector for the ILC.

In Section 2 we outline some of the physics windows which may be opened by a state-of-the-art vertex detector system. In Section 3 we consider the general principles underlying the design of all vertex detectors based on silicon pixels, and in Section 4 we consider means to avoid pitfalls that could be associated with a tracking system of such unprecedented granularity (~10^9 pixels). Finally, in Section 5 we discuss ideas for moving forward from the vibrant multi-stranded R&D activities now under way, to converge on the one or two detector systems to be used at the startup of the ILC, and we touch on the question of longer term upgrades.

2. PHYSICS OPPORTUNITIES

As early as 1991, pioneering studies of what are now called Particle Flow Algorithms (PFAs) had revealed that it would frequently be possible to reconstruct jets sufficiently cleanly to reveal the Feynman diagram underlying the event

[1]. However, in the multi-jet environment to be expected in the TeV regime, for events associated both with Standard Model (SM) and Beyond Standard Model (BSM) physics, separating signal from background would frequently be impossible due to confusion between different physics processes having the same jet multiplicity, and due to combinatorial background within events. These problems could be greatly reduced for many interesting processes, if the leading heavy quarks in jets could be identified. Since many reactions (eg SUSY production) would have small cross-sections, much higher tagging efficiencies would be needed for charm and *b* quarks and tau leptons, than was achieved at SLD. Furthermore, heavy quark sign selection, via measurement of the 'vertex charge', the net charge associated with the tree of secondary and tertiary vertices in a jet, offered additional physics possibilities.

The production of *W*s, Z^0s and top quarks will be associated with much of the new physics, so it is natural to begin by considering how these can profit from advanced flavour ID capability. In terms of event fractions, the Z^0 decays 15% to $b\bar{b}$ and 12% to $c\bar{c}$, so a healthy 27% of decays can benefit from flavour ID. For W bosons, the situation is similar, with 31% decaying to $c\bar{s}$. Many physics studies have focused on leptonic decay channels, which are easily recognised but suffer from a number of disadvantages. For the Z^0, the much larger parity violating coupling asymmetries A_b = 0.94, and A_c =0.67, compared with A_l = 0.15, offer enhanced physics opportunities for the hadronic decays. For the *W*, the missing neutrino in the leptonic decay results in insufficient kinematic information to fully determine the events, which in some cases will be lost in background. However, we are not concerned with a question of hadronic vs leptonic channels. Both are needed in any new physics scenario. For example, there are about 100 parameters in the Minimal Supersymmetric Standard Model (MSSM), and all possible event observables will be needed. If Supersymmetry (SUSY) is realised in Nature, we will need to explore angular distributions in all decay channels, not only the leptonic ones. The use of vertex charge is relatively uncharted territory, but, as will be seen, it has recently become well established by successful physics analyses in SLD [3, 4]. Let us start by looking at a few physics examples, starting with the simplest SM process, having the largest cross-section of all.

2.1. $e^+e^- \to q\bar{q}$

This process, measured with left- and right-hand polarised electrons at maximum $\sqrt{s}$, is a powerful probe of BSM physics [5]. There is sensitivity in the differential cross-sections to Z' states, leptoquarks, R-parity violating scalar particles, and extra spatial dimensions. Figure 1 shows an example of the differential cross-section and A_{LR} for the processes $e^+e^- \to b\bar{b}$ and $e^+e^- \to c\bar{c}$. Notice that the sensitivity to new physics is all in the low cross-section backward region; a clean assignment of the quark charge is essential in order to distinguish between forward- and backward-going *b*- or *c*-jets. Such a measurement would be technically far simpler for muon pairs, but in that case the asymmetry is much weaker, not being measurable even with 1 ab^{-1} of data.

2.2. Chargino and neutralino angular correlations

Consider the process $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$, with decay $\chi_2^0 \to \chi_1^0 q\bar{q}$. Studies to date have focused on the leptonic channels [6-8], quark pairs having been disregarded since the possibility of heavy quark sign selection was not yet apparent. Adding the $b\bar{b}$ and $c\bar{c}$ channels will increase statistics and provide additional physics sensitivity. Typical measurements [9] will consist of forward-backward asymmetries in the $q\bar{q}$ decay angular distributions, which are sensitive to the gaugino parameter M1 and the mass of the left-handed selectron. This is a specific example of the value of complementary measurements in constraining and ultimately determining uniquely the values of SUSY parameters.

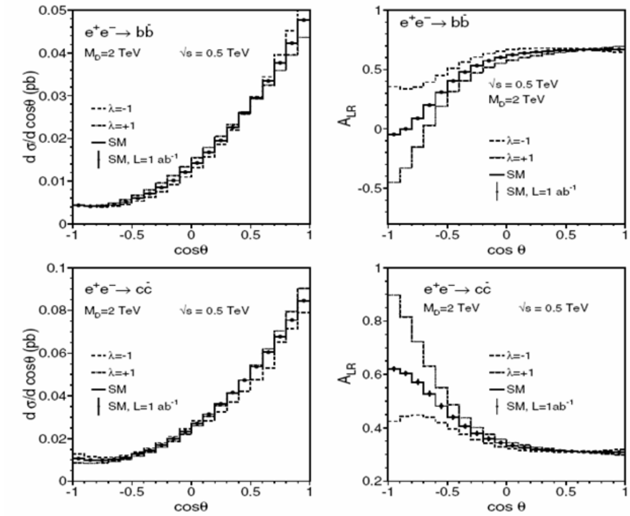

Fig 1 From [5]. Simulated differential cross-section and left-right asymmetries for $e^+e^- \to q\bar{q}$, for SM and large extra dimension processes at 0.5 TeV cm energy

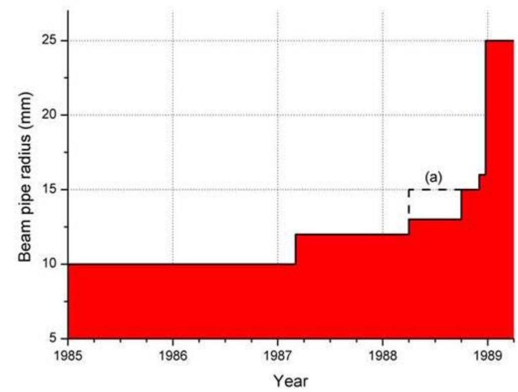

Fig 2 Planned SLD beampipe radius vs time, before installation of the detector in 1990.

2.3. Physics of the top quark

The top quark is unique in being so short-lived that it decays before hadronisation, and long before its spin can flip. For this reason, the polarisation of the top quark at production is reflected in its decay, whereas for the other heavy quarks, depolarisation effects during fragmentation wash out the quark helicities. In the decay $t \to bW$ followed by $W \to c\bar{s}$, the top polarisation can be measured from the angular distribution of the $\bar{s}$ jet with respect to the top flight direction [10]. This jet can be recognised by tagging the *b* and *c* jets in the top decay, with the *s*-quark sign following from that of the *c* or *b* quark. Since the sign-selection needs to be done for only one of the heavy quark jets, it is not required to be extremely efficient.

In principle, the same information can be extracted from the direction and sign of the charged leptons in leptonic *W* decays. However, the hadronic decays will add statistics to generally insufficient event samples, and more importantly will be observed with much smaller backgrounds due to the full event reconstruction (freedom from missing neutrinos which characterise the leptonic *W* decays).

Measuring the polarisation of the top quark will be one of the basic tools for understanding new and unexpected physics in the TeV regime. As just one example, it has been shown [11] that this measurement in $\tilde{t}$ and $\tilde{b}$ decays can be used to determine fundamental SUSY parameters $\tan\beta$ and the trilinear couplings A_t and A_b .

The measurement of $e^+e^- \to t\bar{t}$ at high energy (the study of open top production) will be another powerful pointer to new physics. By measuring production and decay angular distributions and asymmetries associated with different beam polarisation, it will be possible to search for anomalous production and decay form factors, including effects of t-quark anomalous magnetic moment, $t \to b_R W$ decay which is forbidden on the V-A theory, and anomalous $t\bar{t}Z$ couplings [12, 13].

If there is no light Higgs, the process $W^+W^- \to t\bar{t}$ provides a means to probe strong EWSB at the ILC [14, 10]. In order to suppress background processes such as $e^+e^- \to t\bar{t}$ and $\gamma\gamma \to t\bar{t}$, full reconstruction of the top quarks is needed, so the leptonic *W* decays cannot be used. This process is sensitive to the discovery of resonances in *WW* scattering at large $\sqrt{s}$, and their spins can be probed by measuring the top quark polarisation, through the angular distributions of *s*-quark jets in the top decay. Vector resonances (techni-ρ etc) couple to helicity-conserving amplitudes, and scalar resonances (techni-σ) to helicity-flip amplitudes.

2.4. Other examples

Assuming a low mass Higgs boson is discovered, the precision measurements of its branching fractions are of great physics importance, and have long been used as a benchmark for vertex detector performance. However, given that there are two jets from which the flavour can be determined, this is not particularly challenging, even for the $c\bar{c}$ channel. Higgs decay angular distributions, which require the measurement of vertex charge, are more sensitive to the detector performance, as is the measurement of 6-jet processes such as $e^+e^- \rightarrow Z^0HH$, used to determine the very important Higgs self-coupling parameter.

If Supersymmetry is realised in Nature, large CP asymmetries may be observed in the decay of SUSY particles. One example studied in detail [15] is the stau decay process $\tilde{\tau} \rightarrow \tau\chi_1^0 q\bar{q}$. The asymmetry is measured by forming the T-odd triple product $p_\tau.(p_q \times p_{\bar{q}})$, for which the quark sign selection is needed. This is one of many examples in which hadronic decays of the real or virtual *Z* are greatly favoured, because of the larger branching fractions, and the fact that the asymmetry parameter $A_b = 6.4 \times A_e$. The contrast can be dramatic; in one example, a sample of only 1000 staus is needed to observe the CP asymmetry if the $b\bar{b}$ decay can be used, compared with 10^5 required if the measurement is restricted to muon pairs.

The pair production of scalar top particles may be observed by the production of a pair of acoplanar charm jets, from the process $e^+e^- \rightarrow \tilde{t}\tilde{t}$, followed in each case by $\tilde{t} \rightarrow c\tilde{\chi}^0$. This is particularly challenging for the case (which is motivated by physics [16, 17]) of a small mass difference between the stop and neutralino, since the associated charm jets will then have low energy, and be correspondingly more difficult to tag.

While these processes can be used as benchmarks for the vertex detector design, it should be remembered that the ILC will be exploring completely new territory. Previous accelerators have in these circumstances sometimes revealed unexpected new physics, and we can hope for history to repeat itself. The combination of unprecedented performance in both the flavour tagging and jet energy measurement will provide sensitivity to a broad range of new phenomena, which in itself justifies the construction of the best possible vertex detectors and calorimeters. In the case of some large detector systems such as the calorimeter, cost is a serious issue so compromise may be necessary, but a vertex detector based on silicon pixels will always be relatively inexpensive (some millions of dollars, below 0.1% of the ILC cost), so the emphasis of the R&D programme should be to achieve the performance required to do the physics; the cost of producing the vertex detector should not be considered a driving factor.

3. OVERVIEW OF DESIGN AND EXPECTED PERFORMANCE

20 years ago, it was relatively easy to construct a silicon pixel-based vertex detector that was entirely adequate for a broad programme of charm physics in a fixed-target experiment [18]. The Lorentz boost ensured that all decay particles were confined to a narrow angular region, so that a total detector area coverage of 1 cm^2 was sufficient. Momenta were sufficiently high that multiple scattering was hardly an issue. However, the transition to the collider environment was much more challenging. The required solid angle coverage is close to 100% and particle momenta are

greatly reduced. Even at the ILC, the momenta of decay particles in multi-jet events will extend down to below 1 GeV/*c*. Nobody has yet built a truly adequate vertex detector for this environment, but technical progress has enabled a series of upgrades to be made, a trend set to continue through the ILC era. The performance of the SLD vertex detector improved dramatically after it was upgraded from 120 Mpixels [19] to 307 Mpixels [20] in 1996, with the layer thickness being reduced from 1.2% of a radiation length (X_0) to 0.4% X_0.

For the ILC, further major performance enhancements will be possible. First and foremost, it should be possible to reduce the beampipe radius R_{bp} from 25 mm to 12-15 mm. Improved collimation of the beams from the damping rings should eliminate the tails in phase space which plagued the SLC, generating a 'firewall' of synchrotron radiation (SR) as the off-direction particles passed skewly through the final focus (FF) optics. The much longer beam delivery system at ILC will permit improved cleanup of the beams by collimation of any tail repopulation beyond the damping rings. The estimate of 12-15 mm beampipe radius has been stable for the ILC (for both the TESLA and NLC variants) during the past 6 years. However, nothing is guaranteed, and the design value of the SLD beampipe had to be increased dramatically during the last 4 years before machine startup as indicated in Fig 2, due to the experimental discovery by the Mark II Collaboration of these unexpected non-Gaussian tails. Had SLC been able to preserve the originally-planned radius, SLD would probably have been able to make a definitive measurement of the B_s mixing parameter, for which the world of particle physics is still waiting. Similarly, a high performance vertex detector built round a much smaller beampipe at LEP, permitting them to label each jet according to its flavour and quark charge, would very likely have led to a definitive conclusion regarding the existence of the Standard Model Higgs particle within their energy reach.

Given this history, the importance of preserving a small-radius beampipe at ILC should be clear. What has still to be done is to demonstrate the potential physics tradeoffs associated with this parameter, balanced against the choice of the final focus design, the effect on small-angle calorimetry, and so on. While such detailed studies will become possible only when the overall machine and detector designs are much more advanced, it will soon be possible to quantify the influence of R_{bp} on basic physics tools such as the determination of the charge of *b* and charm quarks. This issue goes beyond the obvious advantage of making the first measurement on each track close to the Interaction Point (IP). Enlarging the detector would have other undesirable consequences such as reduced mechanical stability, forcing an increase in the material budget, and possibly requiring 3 sensors rather than 2 in each ladder of the outer layers. This would further degrade the performance by requiring more material within the active volume of the vertex detector, in order to service the inner sensor of each ladder.

As well as benefiting from a much smaller beampipe than at SLD, it should be possible to reduce the layer thickness well below that of the SLD upgrade detector, from 0.4% X_0 to 0.1% X_0 or below. Considerable R&D work is under way in a number of groups round the world, in order to achieve this goal.

The point measurement precision is unlikely to be much better than at SLD (around 3 μm), but the high momentum performance can be considerably improved by a more open geometry (5 layers with large radial steps between each).

Combining these improvements, simulations indicate that the impact parameter precision (for tracks extrapolated to the IP) will be:

$$\sigma_{r\phi} \approx \sigma_{rz} = 3.9 \oplus 7.8/(p \sin^{3/2}\theta)\ \mu\text{m}$$

for tracks of momentum *p* GeV/*c* and polar angle θ in the projections normal and parallel to the beamline respectively, compared with, at SLD:

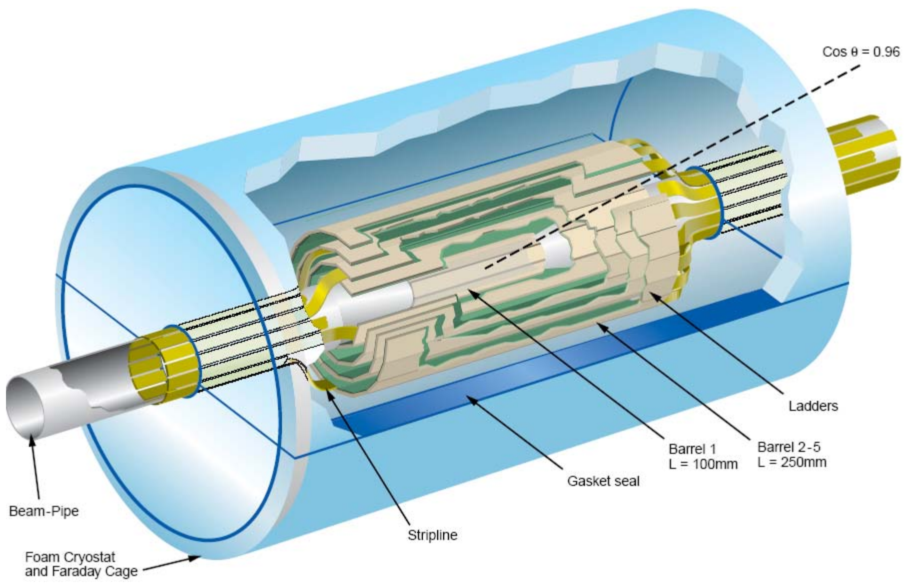

Fig 3 'Long-barrel' option for the ILC vertex detector. The gasket is an almost massless foam construction, entirely negligible if the detector is operated near room temperature. The material associated with the Faraday cage may need to be more significant: see Section 4.3

$\sigma_{r\phi} = 7.7 \oplus 33/(p \sin^{3/2}\theta)$ μm

and $\sigma_{rz} = 9.6 \oplus 33/(p \sin^{3/2}\theta)$ μm.

The generic long-barrel vertex detector layout shown in Fig 3 has been stable for approximately 6 years, and was used as the baseline vertex detector in the TESLA TDR [21]. It consists of 5 concentric layers, the innermost being 10 cm long, and the outer four being 25 cm long. This concept was guided by the assumption of 6-inch wafers, with single sensors on the inner layer, and pairs of sensors, butted together in the middle, for the outer layers. By making the inner layer as long as possible, compatible with the background of electron-positron pairs spiralling out from the IP, one can achieve 3-hit coverage out to $\cos\theta$ = 0.96. This is certainly adequate for most physics purposes, but there may be a case for even greater coverage. The SiD concept study group is considering a more adventurous design (Fig 4) with shorter barrel detectors plus planes of endcap detectors. Which design will prove superior depends on the material budget associated with the ladders used in the barrel, beyond their active length. One suggested layout in this region, for a Column Parallel CCD sensor option, is shown in Fig 5. All sensor types imply overheads in terms of mechanical supports to hold the delicate ladders with micron stability, and some options such as the CCD will require additional ladder-mounted electronics beyond the active area. Other things being equal, the choice of sensor as well as of detector layout may be determined by the amount of additional material required within the sensitive volume (most serious) and at the ladder ends (less serious).

Given that everyone now accepts the need for pixel-based silicon sensors, what are the performance requirements? Monolithic (as opposed to hybrid) sensors are pretty much mandated by the goals for the material budget. The pixels need to be small (about 20 microns square, as used at SLD) to avoid unacceptable cluster merging in the core of high energy jets, particularly on the inner layers [22]. The sensors are subject to ionising radiation in the form of the e^+e^- pair background from the IP, and neutrons from the beam dumps; only moderate radiation resistance is required. Synchrotron radiation, and associated secondary radiation (including fluorescence X-rays) should be at a much lower level than at SLC, due to greatly improved collimation and cleanup of the beams out of the damping rings. The

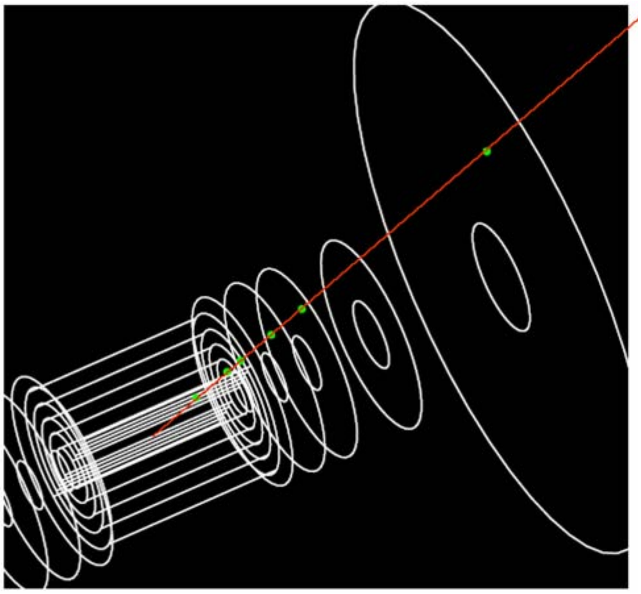

Fig 4 (from SiD Design Study). Vertex detector option comprising a short barrel section and 5 planes of endcap detectors

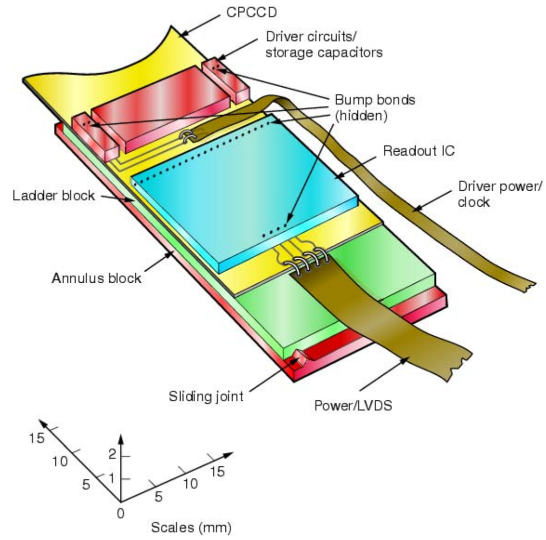

Fig 5 Sketch of mechanical supports and electronics at end of ladder for CPCCDs, one of the many vertex detector design concepts

requirements on readout time are challenging. Integrating the signals through the bunch train, then reading out in the 200 ms available between trains, would be convenient and would correspond to the SLD readout procedure, but would result in intolerably high hit densities due to the pair background, particularly on the inner layers. It appears at first sight to be necessary to read out the detector approximately 20 times per bunch train, in order to limit the hit densities to levels consistent with clean pattern recognition in the track finding. However, we shall return to this point in Section 4.2, where we mention novel architectures which may be able to evade this requirement.

These requirements have stimulated an outpouring of new ideas to overcome the limitations of conventional CCDs as used at SLD, for which the readout times would need to be tens of milliseconds, in order to achieve the required noise performance. Twelve innovative options are currently being considered. For details of these exciting device architectures, which are being developed by people from about 30 institutes around the world, the reader is referred to [23]. While space does not permit even a brief description of all these architectures in this paper, there are certain fundamental features, common to all of them, which explain why silicon pixels have 'captured the market' for future vertex detectors, a field which in the past was dominated by microstrip detectors. We summarise the key features in the following paragraphs.

Firstly, a high energy minimum-ionising (min-I) particle traversing a condensed material such as silicon, generates a dense trail of electron-hole pairs, approximately 80 per μm of path length. However, this ionisation derives from only approximately 4 primary collisions per micron, with wildly fluctuating energy loss, depending on whether the particle excites M-shell, L-shell or K-shell electrons, the first-named being by far the most prolific, in the form of 17 eV plasmons. As discussed in [24], the energy loss distribution in thin silicon detectors differs markedly from a Landau curve. To be fully efficient for min-I detection, much thicker samples are required and much lower thresholds need be set, than would be expected for Landau-distributed signals. Thin active layers are certainly desirable in order to retain good precision when measuring oblique tracks, but a lower limit of around 20 μm is set by considerations of efficiency

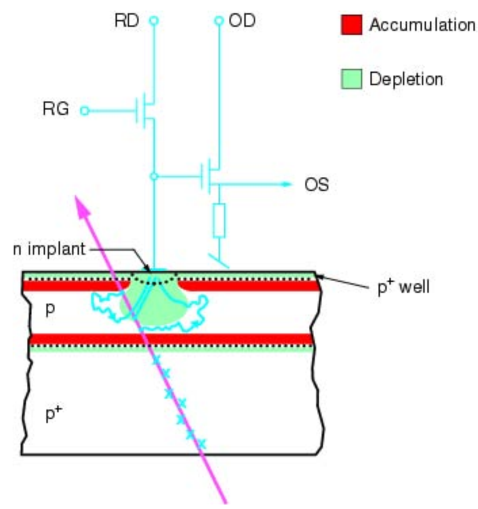

Fig 6 Cross-section of a generic sensor architecture in which the signal electrons diffuse between the upper and lower reflective layers, until they are captured in the depleted regions associated with the collection node (gates or reverse-biased diode) built into the pixel structure

for tracks with normal incidence. The precise value of the thickness required will of course also depend on the noise performance of the chosen sensor technology.

Secondly, extreme mechanical thinning of sensors to 10 µm or below, while it is regularly undertaken for back-illuminated CCDs where one of the goals is maximum quantum efficiency, is neither required nor desired for a vertex detector. A silicon sensor of thickness around 50 µm is much more easily handled, can be made into a robust ladder with appropriate backing material (silicon carbide foam is a current favourite, but there are many options), and the assembly can probably achieve the desired goal of 0.1% X_0 in material budget. While the sensor can be made thick enough for convenient handling and assembly procedures to be used, a thickness of about 20 µm for the sensitive layer can be achieved by using epitaxial material, as indicated in Fig 6. The difference in doping density between the epi layer and the highly doped substrate results in a thermally-induced potential barrier between the two layers, even if both are biased to the same potential. Electrons liberated in the substrate, where the minority carrier lifetime is extremely short, recombine immediately. However, those liberated in the epi layer, where the carrier lifetime can be long, are able to travel long distances within this layer, and feel a near-perfect reflective barrier whenever they approach the *p/p+* interface. Most of the sensor types under consideration exploit this feature, for collection of signal charge. In the example shown, an implanted *p*-well provides a second reflective barrier covering most of the top surface, apart from a matrix of small apertures through which positively biased *n*-implants create depletion regions below the reverse-biased *p-n* junction. Signal charge that diffuses to the edge of one of these regions will be collected rapidly by drift in the internal field below the junction.

These features, together with the immense power of deep submicron silicon processing, have led to a long list of pixel-based detector designs which may be of interest for vertex detectors at the ILC: CCDs with CMOS readout, CMOS sensors, CMOS sensors with embedded CCD registers, SOI-based designs, DEPFET pixels, and more besides. However, it may be that not all design concepts can be made to work. The ILC will be a challenging environment for a Gigapixel-scale system, not least because of possible electromagnetic interference, to be discussed in the next Section.

Regarding physics performance, this should be rather independent of the pixel architecture, provided that the general features discussed above can be realised. The first requirement is of course the tagging of *b* and charm quarks, as well as tau leptons. Figure 7 shows and example of what can be achieved. For *b*-tagging, the performance is only slightly

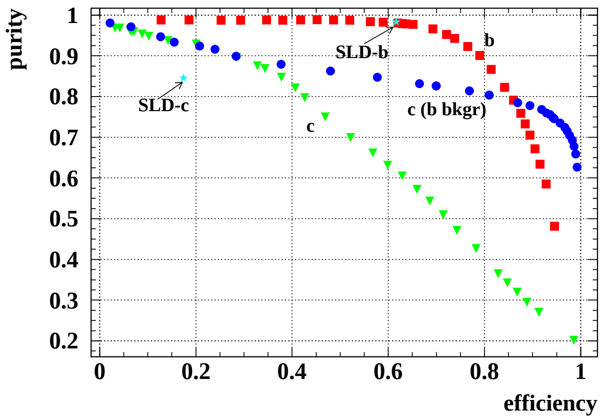

Fig 7 (from [22]). Efficiency-purity plot for the benchmark process $e^+e^- \to Z^0 \to q\bar{q}$ at $\sqrt{s} = 92$ GeV

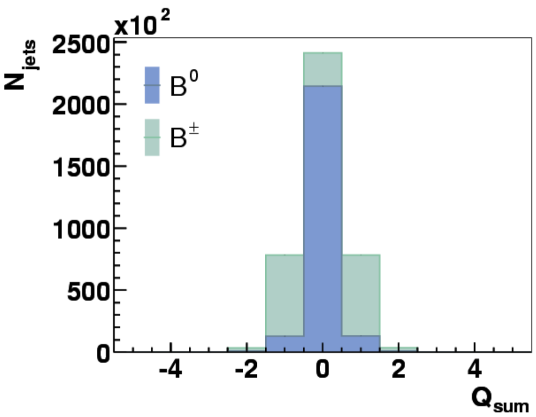

Fig 8 (from [25]). Preliminary indication of vertex charge purity achievable in the process $e^+e^- \to b\bar{b}$ at $\sqrt{s} = 500$ GeV

better than at SLD, which was close to asymptotic in this regard. However, for charm tagging, there is a marked improvement. The case of a charm tag in the absence of a large light-quark background is interesting, since it corresponds to such situations as top quark decays, where tagging a charm jet from the *W* decay permits a clean measurementof the top quark polarisation. Such events will be analysed using the *b*-tag from the top decay, and the reconstructed invariant masses of the top quark and *W*, so backgrounds will be low; the main additional requirement beingto distinguish between the charm jet and the *s*-quark jet from the *W* decay.

As previously noted, there are numerous physics examples where knowledge of the charge of the leading quark in the jet will be an important tool. This has been established in SLD, for example in the most precise measurements of the parity-violation parameters A_b and A_c [4]. Not only that, but this measurement is also a very sensitive parameter for understanding and tuning up the track-finding code. Even a very low level of missed tracks will create unphysical values ± 2 for the measured vertex charge, beyond the populations expected due to decay tracks merged with the IP and other legitimate sources of mis-assignment. Figure 8 indicates the performance levels currently being achieved in simulations [25]. As can be seen, the majority of charged and neutral *B*s are recognised as such. The charged category leads unambiguously to the correct quark charge, while some of the neutrals can also be used via the 'charge dipole' procedure pioneered in SLD [3]. However, these studies are at an early stage. The performance will improve as procedures are refined, but will also be degraded as a fully realistic simulation is developed (including effects of background on the cluster centroid determination, non-Gaussian tails on multiple scattering, etc). So these results are not yet ready to be used in quantitative physics studies, but the performance goes well beyond what was achieved at SLD, where the physics benefits were considerable.

4. ELECTROMAGNETIC INTERFERENCE AND NOISE REDUCTION

Detector systems often experience problems of electromagnetic interference (EMI or pickup) in collider experiments. Diligence in terms of grounding and screening can ameliorate many problems, but there can still be nasty surprises. The ILC vertex detector, with its tiny signals (around 1000 e-) and huge number of pixels (~10^9) needing to be read 20 times during the bunch train when the beams are crossing at 300 ns intervals, kicker magnets are firing, and other readout systems are active, could be vulnerable.

The SLD experience was that by careful shielding (a re-entrant Faraday cage enclosing the beampipe), grounding (vertex system isolated all the way to the racks in the control room), and benefiting from the electromagnetic screening provided by the massive iron envelope surrounding the detector solenoid, the readout system was extremely quiet when the vertex detector was installed and the overall detector was closed up. However, when the beam was turned on, there were problems. The front-end preamps were thrown into saturation, and a phase-lock loop on the electro-optical converters was disrupted. Fortunately, these recovered within some tens of microseconds, so the readout could proceed smoothly during the 8 ms inter-bunch period. But this experience could provide an important warning for the future. Comparable effects at the ILC would disrupt readout throughout the train. However, an interesting question is whether the SLD effects really were related to the beam, by wakefield RF leaking out from the beampipe enclosure. Other theories have been suggested, but seem unlikely. Possible leakage paths have been identified (related to beam-position monitors (BPMs) and beam-size monitors, as well as imperfections in the shielding in irregular or electrically resistive regions such as bellows systems. It is possible that the shorter bunches associated with linear colliders may produce more severe effects. All this is speculative, and one suggestion being considered is to run a test beam through the SLD 'R20 module' (the innermost 2 m length of SLD's beampipe system) and make measurements which were impossible when it was embedded in the overall detector.

For the ILC vertex detector system, a three-pronged approach is suggested. Firstly, one should design, manufacture and test the equipment in the Interaction Region (IR) so as to minimise the leakage of electromagnetic radiation (beam-related wakefields and radiation by kicker magnets and other external systems). Secondly, the design of the vertex detector should be developed to minimise sensitivity to pickup at all frequencies. Thirdly, one should make tests to establish the compatibility between the EMI environment at the ILC, and the vertex detector system prior to installation, improving the shielding if necessary. These suggestions also apply to other systems, notably the tracker, but the very small signals and high channel count of the vertex detector make it the most vulnerable. Let us consider these three aspects in turn.

4.1. Minimising leakage of beam-associated and other RF radiation

Firstly, it is evident that the FF system has the potential to be relatively quiet as regards RF escaping from the beampipe enclosure itself. If one could stipulate that there should be no penetrations into this system, the situation would probably be benign. There are some issues at lower frequencies (around 1 MHz) where the skin depth may be too large to afford complete protection beyond the thin inner section of beampipe, or at some thin-walled bellows systems, but the threat is probably not serious. Similarly, well-made flanged connections between beampipe sections using copper seals are probably safe. Unfortunately, penetrations for vacuum pumps, BPMs, beam-size monitors, connections to kicker magnets, etc will inevitably be numerous at the ILC, as they were at SLC, and this is where the danger lies. In principle, RF escaping down coax cables and light pipes can be contained by high quality connectors and screening, and everything will be contained if the enclosures at the far end are electrically hermetic. However, a poorly assembled connector, or a box with an imperfectly fitting lid, or a power cable being fed to that box through a hole, are some of many routes for RF radiation to escape. There have been examples in the past where design or assembly errors led to a tracking detector being entirely disabled until the problem was found and fixed. The SLD experience was less serious in that a workaround solution could be found. Given the number of beampipe penetrations needed at the IR of the ILC, and the high wakefield power generated due to the irregular profile of the interior of the beampipe in this region, one should be careful. Experts agree that simulations are not very useful, given the complexity of such systems, and in any case are not going to predict the effects of human error. An incorrectly fitted coax connector can permit severe RF leakage, and this radiation can bounce around in the interior of the detector, reflecting off metal surfaces, so that the source is difficult to pin down. However, there should be an excellent window of opportunity for dealing with such problems. At SLC, there was a commissioning period for the machine before any detector was allowed on beamline. Enclosed in a blockhouse, the FF region was equipped with an assembly of diagnostic equipment that had later to be removed in order to accommodate the Mark II detector. Assuming that the ILC will need a similar commissioning phase, this will permit a complete survey of escaping RF radiation in conditions where diagnostic equipment will have convenient access, followed by corrective measures as required. As a result of this phase, a quantitative measurement of the irreducible level of RF leakage will have been established. Such an opportunity would be irretrievably lost were the detector to be moved onto the beamline without making these measurements.

4.2. Minimising detector sensitivity to RF radiation

Prior to these measurements during ILC commissioning, prototype ladders made with the candidate detector technologies should have been calibrated for RF sensitivity. Based on experience in other fields (notably space-based electronics used in communications systems [26]) it is to be expected that the large ICs which comprise the vertex detector pixel arrays will be subject to internal RF fields generated either by external radiation falling on the surface of a ground plane and inducing a response in the interior (via crawling or surface waves) or by radiation impinging on the side of the IC and exciting the structure to multiple resonant modes corresponding to its characteristics as a waveguide assembly (typical frequencies 1 to tens of GHz). These internal electromagnetic fields may couple to the in-pixel circuitry directly or via power distribution or signal lines which may run the full length of the device, forming effective antennas. While this frequency range should in principle be above the bandwidth of the signal sensing circuits, there is typically a problem in achieving the desired bandwidth limitation in these circuits, due to the fact that high value resistors cannot be made in the CMOS process, and in-pixel capacitors need to be physically very small.

Each technology option for the vertex detector will have different thresholds for being disrupted by EMI. One of them (the In-Situ Image Storage device, or ISIS) is designed to be as robust as possible [27, 28]. It evades the problem of disruption during the bunch train by storing the accumulated signal charge in a 20-element linear CCD structure, one element for each 50 μs time slice of the train. Since charge stored in the buried channel of a device is extremely difficult to disrupt, it will be retained through the train, available for leisurely charge-to-voltage conversion and readout during the quiet inter-train period of 200 ms. Another attractive option regarding robustness to EMI, is the Fine Pixel CCD [29]. Other options may be more or less sensitive to interference during the critical bunch train of 1 ms duration. The RF susceptibility of each architecture can be measure by testing a fully equipped ladder with its associated ILC-compatible electronics. These measurements should be made in a standard calibrated test enclosure, and the test results, along with the other characteristics such as efficiency and precision for min-I particle detection, material budget vs polar angle etc, used to select the options with which to construct the real detector.

4.3. Matching the environment to the detector sensitivity

By the time of ILC commissioning, the vertex detectors will have been built with the chosen technologies. What if the RF level identified in the accelerator tests exceeds the limit for a chosen technology? The answer which at first sight seems obvious is to enclose the detector in an adequate Faraday cage, as was attempted at SLD. However, it is notoriously difficult to construct a Faraday cage which provides significant attenuation of high frequency radiation. Many examples used in our field are 'little better than dust covers' [30]. In the case of SLD, the Faraday cage was quite a sophisticated construction, in the form of a re-entrant or donut configuration, including a thin beryllium shell external to the beampipe. Its most significant deficiency was the presence of slits to permit the passage of striplines carrying power and amplified signals. These created effective slot antennas, permitting currents to flow on the inside of the cage, hence providing apertures for the penetration of RF radiation to the interior of the enclosure. In future, it will be possible to do better in three ways. Firstly, the data sparsification will take place on-ladder, so the need for external connections will be greatly reduced. Secondly, these apertures will be minimised, and high quality RF connectors and double screened coax could be used to deliver power to the detector. Thirdly, the inner surface of the cage could be coated with an RF-absorbent layer using materials such as those developed for radar-avoidance systems for stealth aircraft. While such measures can be effective, they would imply a possibly severe increase in the material budget. It would therefore be preferable if possible to retain the lighter but less effective alternative, as was used at SLD. However, in the relatively short time between the machine commissioning and the detector moving on beamline, substituting a more robust Faraday cage would certainly be a practical option. If as a result the tracker performance is significantly degraded by the required enclosure, this will provide the stimulus to build an upgrade vertex detector with a more EMI-resistant technology.

4.4. Noise and pickup reduction via correlated double sampling

As well as the issue of robustness against EMI, dealing with the 10^9 tiny signals from thin epitaxial silicon may need careful noise reduction techniques in order to avoid a 'data deluge'. The term widely used for the optimal procedure is Correlated Double Sampling (CDS), which was originally developed as a form of pedestal subtraction in CCD readout systems, where *kTC* noise from the node reset would otherwise have been the dominant noise source [31]. As shown in Fig 9(a), the procedure normally used in imaging applications (eg astronomy) is to follow each node reset by a period of pulse shaping (ideally analogue or digital integration), then store the measured amplitude. This is followed by the transfer of the signal charge to the node, and an identical sampling procedure, with the analogue or digital difference being a measure of the pixel signal charge. Then there follows another node reset, and the procedure is repeated for the next pixel. It is important to match the signal shaping time or integration time to the readout frequency. If the shaping time is too long, the signal amplitude will be reduced, with consequent degradation in noise performance. If it is too fast, the sample will be subject to excessive high frequency noise, again degrading the performance.

For sparse data scenarios, such as we encounter in particle tracking detectors, the same performance can be achieved by resetting the node only occasionally, typically in CCD systems at the start of a new row, see Fig 9(b). In such an integrating mode of operation, the signal in each pixel is evaluated by subtraction from the previous level. This procedure depends on the analogue circuit remaining below saturation until the time of the next reset. It is mathematically equivalent to the standard CDS in terms of noise suppression, but provides an additional bonus in cases of sparse data. High frequency pickup capacitively coupled to the charge sensing circuit can induce a spurious signal. However, due to the capacitive nature of the link, the spurious signal will usually die away rapidly, giving an anomalous pattern of signal values, as indicated by the mid-trace excursion of Fig 9(b). This sampling procedure therefore provides information beyond that associated with the standard CDS approach, where one evaluates the difference {signal plus pedestal} - {pedestal}, and any further information is effectively lost at every node reset. In the

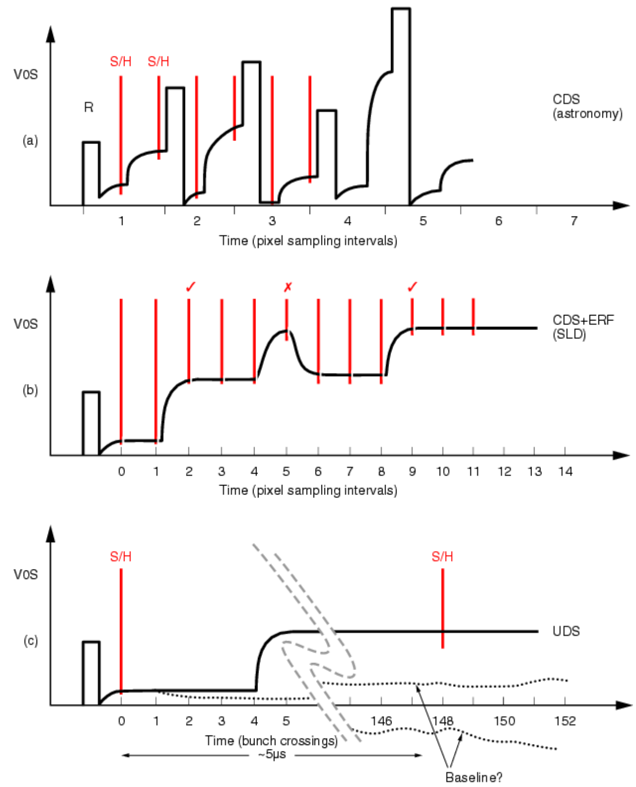

Fig 9 (a) CDS as used in astronomy, with a reset pulse after every pixel

(b) as used in particle detection, where the sparse data permits infrequent resetting, limited only by the linear range of the electronics

(c) a dangerous variant, in which the signal is determined with respect to a much earlier measurement of the pedestal; this could be called Uncorrelated Double Sampling

modified approach, one can in addition form the difference which straddles these signals, and take the true signal to be the smaller of the two differences. The benefit of this 'Extended Row Filter' in SLD [20] was a reduction in the trigger pixel rate by about a factor 100 at the threshold of ~200 e- needed for efficient min-I particle detection.

These procedures are likely to be of value in the more challenging ILC environment. However, some technology options tend to adopt a loose definition of CDS which leaves them open to possibly severe problems of pickup and pedestal drift as indicated in Fig 9(c). Their intention is to achieve the time slicing by sampling the potential of the sense node (gate or diode) every 50 µs. A sufficiently fast shaping time (~100 ns) is still needed in order to sense a hit from the bunch crossing just preceding the sample. However, there is now a large difference between the shaping time and the period between samples, so the circuit is sensitive to baseline drift resulting from the effects of *1/f* noise, external slow and fast pickup, etc. There are of course ways round this in principle, for example by doubling the number of storage capacitors, and using the signals stored on the dummy channel of each pair to subtract pickup. However, this design concept may run into a different problem due to unacceptable noise, in the front-end transistors, which are added in quadrature between the signal and dummy channels.

In short, it could be that some of the architectures being pursued may run into difficulties as regards pickup suppression and noise performance under ILC readout conditions. However, there are always new ideas, and it would be premature to rule anything out at this stage.

5. GETTING TO THE ILC, AND BEYOND

There are currently many groups pursuing an expanding range of technology options for the ILC vertex detector. It is widely hoped that there will be two overall detector systems, for which there are a number of compelling arguments, and in this case there should surely be two different vertex detector technologies, to minimise the risk of failure of any one of them in this challenging and novel environment. Whatever results are obtained in test beams, there will be sufficient uncertainties to make it too dangerous to pick a single winner. But how to pick the top two, out of the dozen or so options currently being investigated? Firstly, good advice to the yet-to-be-formed proto-collaborations must be to refuse to be rushed into a decision. The vertex detector construction cost will need to be some small number of millions of dollars, so the choice between options will not have a major impact on cost of the overall detector. It has been informally stated among the vertex detector R&D groups that they aim to have full-scale ladders operating in test beams by about 2010, by which time collaborations may be firmly in place, and these tests should provide sufficient information on which to base their decisions. If the overall ILC schedule would slip, this decision time should move accordingly. It is already pretty clear that some of the new options are unlikely to reach the stage of full ladders by 2010, unless R&D funds start to ramp up strongly. If the overall schedule holds, these options may need to complete their development work with an eye to being considered for possible upgrades. Given the risk that challenges such as EMI may force compromises such as bulky Faraday cages on the simpler options, it may be really important not to let the R&D programmes lose momentum as soon as the first one or two vertex detector options have been selected. Some options are also being developed for other applications, such as X-ray telescopes, synchrotron radiation detectors for XFEL facilities and the like, so maintaining their R&D programmes may not require particle physics support.

Since LCWS 1993, pixel-based silicon detectors have provided the only candidates for the ILC vertex detector. Can we be sure that this is the only approach to be considered? Well, there is always room for a new idea. At the time of the SLC Workshop in 1982, one of the front-running options was a rapid-cycling bubble chamber [32]. Silicon microstrip detectors and CCDs were regarded as possibilities, but were generally regarded as extremely speculative. That was about a decade before the startup of SLD, and a great deal happened during those ten years. Since the ILC is at least ten years away now, there is still time to pursue some novel ideas. To anyone who thinks of something revolutionary, my advice would be not to take too seriously the opinions of experts. At the time when silicon pixels in the form of CCDs were first considered for vertex detectors in 1979, there was a great deal of scepticism from the established silicon detector community. With hindsight, this can best be explained by the fact that many of them believed that if it were a good idea, it would surely already have been thought of by a silicon detector 'insider'. Fortunately, some experts such as Gatti, Gursky, Kandiah, Radeka and Rehak gave their enthusiastic support, without which it would not have been possible to even start the R&D activities.

In conclusion, I would like thank those great experts, as well as the many who have become experts more recently, particularly the young physicists and engineers now driving this field forward. There is a small international army which has made the development of vertex detectors for the ILC extremely dynamic. While the atmosphere is one of competition, it is most certainly friendly. Once technology the decisions have been made, it is to be hoped that the talented people who have contributed to this great adventure on a world-wide basis will form fully international teams in which the previous boundaries will be forgotten, and everyone will work together to construct these wonderful new tools which will carry us, in conjunction with the LHC, to the next major advances at the energy frontier of particle physics.

References

[1] D.L. Burke, Proc LCWS 1991 Saariselka, World Scientific (1991) 51
[2] C.K. Bowdery and C.J.S. Damerell, Proc LCWS 1993 Hawaii, World Scientific (1993) 773
[3] T.R. Wright, SLD thesis, SLAC-Report-602 (2002)
[4] K. Abe et al, Phys Rev Letters 94 (2005) 091801
[5] S. Riemann, ECFA-DESY preprint LC-TH-2001-007 (2001)
[6] G. Moortgat-Pick and H. Fraas Phys Rev D 59 (1999) 105016
[7] S.Y. Choi, H.S. Song and W.Y. Song Phys Rev D 61 (2000) 075004
[8] TESLA TDR, DESY 2001-011 (2001) III-64
[9] G. Moortgat-Pick, A. Bartl, H. Fraas and W. Majerotto, hep-ph/0002253 (2000)
[10] E. Ruiz Morales and M. Peskin Proc LCWS 1999, Sitges, University of Barcelona publication (2000) 461
[11] E. Boos et al, hep-ph/0303110
[12] M. Peskin LC lectures (SLAC) March 2002
[13] TESLA TDR, DESY 2001-011 (2001) III-146
[14] T. Barklow, Proc Snowmass Workshop 1996, SLAC Pub (1997) 819
[15] A. Bartl et al, hep-ph/0306304
[16] J. Feng, presentation at LCWS 2005 Stanford U, to be published
[17] C. Milstene, presentation at LCWS 2005 Stanford U, to be published
[18] C.J. S. Damerell, Proc Physics in Collision Iv (1984) 453 (Editions Frontieres, Gif-sur-Yvette, France 1985)
[19] G.D. Agnew et al, Proc 26th Conf on High Energy Physics, Dallas, Vol 2, World Scientific (1992) 1862
[20] K. Abe et al, Nucl Instr and Meth A 400 (1997) 287
[21] TESLA TDR, DESY 2001-011 (2001) IV-14
[22] S. M. Xella Hansen et al ECFA-DESY preprint LC-PHSM-2003-061 (2003)
[23] Vertex detector parallel session presentation at LCWS 2005 Stanford U, to be published
[24] C.J. S. Damerell, Rev Sci Instr 69 (1998) 1549
[25] S. Hillert, presentation at LCWS 2005 Stanford U, to be published
[26] J. Eastwood, Culham Electromagnetics and Lightning, and B. Ellison, RAL, (private communications)
[27] C.J.S. Damerell, LCWS 2004 Paris, to be published
[28] K.D. Stefanov, presentation at LCWS 2005 Stanford U, to be published
[29] Y. Sugimoto, presentation at LCWS 2005 Stanford U, to be published
[30] Marvin Johnson, Fermilab (private communication)
[31] M.H. White et al, IEEE J Solid-State Circuits, SC-9 (1974) 1
[32] Proc SLC Workshop on Exptl Use of the SLAC Linear Collider, SLAC-Report-247 (1982) 184