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R&D Challenges of a CLIC Vertex Detector

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The Compact Linear Collider (CLIC) is a concept for an electron-positron collider with a center-of-mass energy of up to 3 TeV. Given the unprecedented experimental conditions at CLIC none of the technologies available today can fulfill all requirements set for the vertex detector. At the conference these conditions and the challenges they pose for the R&D of a CLIC vertex detector were presented.

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1. Introduction

To understand the challenges for the R&D of a vertex detector we start with the physics expected at a multi-TeV linear e^+e^- collider. There are several theories covering the open questions in particle physics at the moment: the Standard Model (including an unconfirmed Higgs sector), supersymmetry, extra dimensions, and more. The LHC will hopefully determine what may or may not lie beyond the known physics. In case new physics is discovered in the energy range of the LHC then an e^+e^- collider up to several TeV would be an excellent tool to study that physics in more detail. In [1] an overview is given for the physics prospects at CLIC.

One challenge faced with multi TeV physics is its topological distribution. For many production channels the cross sections for s-channel processes decrease with the center-of-mass energy while for the t-channel processes they increase in this energy regime. With the latter being predominantly forward-boosted, operating CLIC at several TeV will mean that many of the interesting events will be in the forward region of the detector. The sub-detectors in this region, including the vertex detector, thus deserve extra attention. For an elaborate study on forward tracking the reader is referred to [2].

2. Requirements for vertex detector

The main objective of the vertex detector will be the measurement of secondary vertices in order to do flavor tagging. From the experience in the ILC community, see [3], this objective has been determined to be achievable with a transverse impact parameter resolution $\sigma_{R\phi}$ of

$$\sigma_{R\phi}(p_T) = \sqrt{a^2 + \frac{b^2}{p_T^2 \sin\theta}} \quad \text{,with } a = 5\ \mu\text{m and } b = 15\ \mu\text{mGeV}. \tag{2.1}$$

In this equation θ is the polar angle. Parameter a gives the high energy resolution and is driven by the point resolution of the detector. The low energy resolution parameter b is driven by the multiple scattering.

3. e^+e^- collisions at CLIC

The basic idea behind the CLIC accelerator concept is to use a low energy, high intensity beam to drive a high energy, low intensity beam. The first beam serves as an RF source, the latter is used for the collisions and is accelerated by normal conducting RF cavities operating at a gradient of 100 MV/m. The main beam consists of trains of bunches. To obtain a luminosity as high as possible, each train has 312 bunches separated by 0.5 ns. The repetition rate of the trains is 50 Hz, implying a quiet time of 0.02 seconds between trains.

In Table 1 we summarize the CLIC beam parameters and state for comparison the same parameters for LEP 2 and for ILC at 0.5 TeV center-of-mass energy. The ILC is another concept for an e^+e^- collider, which is based on superconducting RF cavity technology, see [3]. With an accelerating gradient of 32 MV/m it is aimed to operate at a center-of-mass energy up to 1 TeV. The crossing angle mentioned in the table is needed for linear colliders to be able to separate the in- and out-coming beams after crossing.

PoS(VERTEX 2010)041

	LEP 2	ILC 0.5 TeV	CLIC 3.0 TeV
Peak luminosity [cm^{-2}s^{-1}]	$1.0 \cdot 10^{32}$	$1.5 \cdot 10^{34}$	$2.0 \cdot 10^{34}$
Bunch crossing separation	$\sim 22\ \mu$s	369 ns	0.5 ns
Bunch crossings per train	4	2670	312
Train repetition rate	50 kHz	5 Hz	50 Hz
Crossing angle [mrad]	–	14	20
Bunch charge [$\cdot 10^9$]	30	20	3.7
IP size σ_x	250 μm	600 nm	45 nm
IP size σ_y	5 μm	6 nm	1 nm
IP size σ_z	10 mm	300 μm	40 μm
Coherent pairs at IP / BX	negligible	$< 10^2$	$3 \cdot 10^8$
Incoherent pairs at IP / BX	negligible	$1 \cdot 10^5$	$1.5 \cdot 10^5$
$\gamma\gamma \rightarrow$ **hadronic events / BX**	negligible	0.2	3

Table 1: *CLIC parameters, as in [4]. For comparison the parameters for LEP 2 and for the ILC with center-of-mass energy of 0.5 TeV are also given. At the bottom the expected number of background events is given, see Sections 3.1 and 3.2. IP stands for interaction point, BX for bunch crossing.*

The small bunch length of 40 μm at the Interaction Point (IP) at CLIC means that the locations of different collisions in one train cannot easily be resolved. Assuming the worst, that is none can be resolved, we have that the time-stamping capability of the detector defines how many bunch crossings overlap in one readout event. For example: a time stamping of 20 ns, corresponding to the current state-of-the-art in vertex detector technology, corresponds to 40 bunch crossings overlapping.

Lepton colliders are often stated as ‘clean’ colliders where the ratio of signal to background channels is relatively high. This was indeed the case for LEP. However, with higher energy beams several background processes arise, see also [5]. We will discuss two: beamstrahlung and $\gamma\gamma \rightarrow hadrons$.

3.1 Beamstrahlung

Beamstrahlung is the consequence of the electrons and positrons in both beams attracting each other at the moment of crossing and increases with the beam energy. As with any other means of acceleration, the bending causes the particles to radiate photons. A benefit of the phenomenon is an auto-focus of the beams, decreasing their widths and increasing the luminosity. A disadvantage is a decrease in the center-of-mass energy of the beam collision. Another disadvantage is the creation of background electron-positron pairs by the photons. The following types of pairs are defined:

- **Coherent pairs** are produced when a real photon interacts with the coherent field of the bunch. With 1.5 TeV beams approximately $3 \cdot 10^8$ pairs are produced per bunch crossing. Most of these pairs leave the detector down the outgoing beampipe and will therefore be neglected in these proceedings.

- **Trident pairs** are similar to coherent pairs, except that the pair originates from a virtual photon [6]. At the time of writing their consequences for CLIC are still under study.
- **Incoherent pairs** are produced when the photon interacts with an electron or positron in the bunch. At 3 TeV center-of-mass energy approximately $1.5 \cdot 10^5$ pairs are produced per bunch crossing. This is a large source of background hits in the vertex detector and has been studied in great detail.

For the coherent and incoherent pairs the production rates are obtained from [7] which used the GUINEA-PIG generator [8]. Many of these pairs are steered down the beampipe by the strong magnetic field. The field originates from the detector's solenoid and will be 4 to 5 Tesla. In Section 4.1 we come back to the hits as a consequence of incoherent pairs. Studies of the trident pairs at CLIC are underway and first results show that their flux through the detector layers is relatively low [9]. We can therefore safely neglect them here in the background analysis.

3.2 Hadronic events

At center-of-mass energies of a few TeV the cross-section for processes of the type

$$e^+e^- \rightarrow e^+e^- + \gamma\gamma \rightarrow e^+e^- + hadrons$$

becomes substantial, resulting in approximately 3 hadronic events per bunch crossing at CLIC. These results are obtained using the GUINEA-PIG generator combined with PYTHIA [10].

Being mostly produced in the forward region of the detector, we show in Fig. 1 the hit density on forward tracking disks positioned at five different z values as a function of the radial distance. From these results it can be concluded that the hit density is approximately an order of magnitude lower than the density caused by the incoherent pairs. For these proceedings the hadronic channels are therefore neglected.

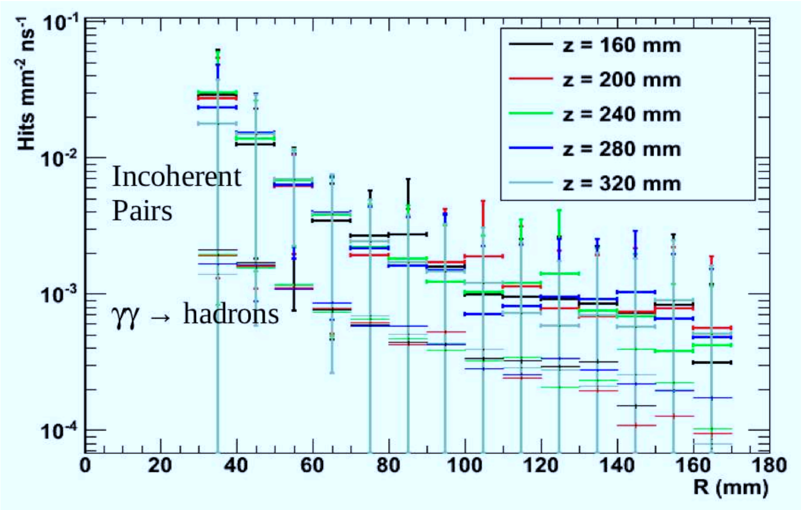

Figure 1: *Hit density during the beam bunch train on disks as a consequence of incoherent pairs and hadronic events, obtained from [11], at a center-of-mass energy of 3 TeV.*

4. Vertex detector concept

In 2009 two detector concepts for the ILC, named SiD [12] and ILD [13], were validated by scientific review. The CLIC study has taken the two designs as a baseline for detector research and is working now together with the ILC concepts to investigate the changes needed to adjust them to the experimental conditions at CLIC.

The consequences of the beamstrahlung trident pairs and incoherent pairs are being studied. For now, however, only results with incoherent pairs are available.

4.1 Hit density in vertex detector

To reduce the particle flux from beamstrahlung in the first layer of the vertex detector its inner radius is extended from 15 mm as designed for the ILC to 30 mm for CLIC, see [14]. As in the ILC designs, the beampipe at CLIC has a conical shape in the forward regions where the background particle flux extends to a higher radius.

In Fig. 2 the particle density is shown as a function of time, starting with the arrival of the first bunch of a train. For this study the incoherent pairs from a full bunch train were simulated in the full detector simulation program MOKKA [15], see [7]. We see in the figure how after approximately 20 ns the density increases; this is caused by particles back-scattered from the forward detector.

If the vertex detector had to integrate over all the particles from a complete bunch train, i.e. over 156 ns, the particle density would correspond to 5.4 mm^{-2} in the innermost layer. The consequences for the detector occupancy are severe: assuming for example $20 \times 20\ \mu\text{m}^2$ pixel sensors,

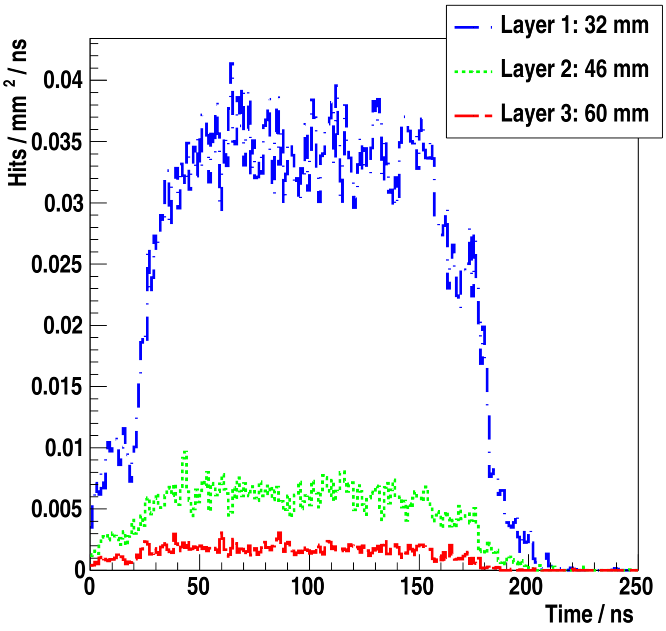

Figure 2: *Particle density from incoherent pairs as function of time in a detector model with three barrel layers at 32, 46 and 60 mm. A minimum energy deposition was required from a particle traversing the silicon sensor and one hit corresponds to one particle. Cluster formation from one particle traversing a layer is thus not taken into account.*

with 5-10 pixels hit per particle traversing a sensor, the innermost layer has an average occupancy of 1-2% during the 156 ns of a train. Moreover, these results are the average after integrating over the azimuthal angle. Due to the 20 mrad crossing angle of the two beams the back-scattered particles are not homogeneously distributed over the vertex detector and hot spots with approximately five times higher densities are present.

Studies with different designs of the beampipe are underway to reduce the flux of back-scattered particles in the sensor layers. Nonetheless, to be able to resolve the vertices in a single event, a time-stamping will be required to identify hits belonging to the same event, or at least to a time-window integrating over not too many events. A timing accuracy of 5 to 10 ns is probably needed.

4.2 Strawman design

The vertex detector suffers most from the higher flux of beamstrahlung produced at CLIC. Taking into account that much of the interesting physics is to be expected in the forward region, currently a complete new strawman design is under investigation for CLIC.

A three-layered barrel structure of 13 cm half-length is considered, carrying pixel sensors on both sides of the layers. This is complemented by a closely packed end-cap of three disks with the same doublet pixel technology.

The choice of double-layers reduces the total amount of material for support. Such design also satisfies the desire to have the hits as close as possible to the interaction point for optimal impact parameter resolution at high energies. Moreover a double sided layer with two hits can form mini-tracks; extrapolating these tracks back to the interaction point can help in vetoing against possible background hits originating from the many beamstrahlung pairs backscattered from the forward region.

4.3 Impact parameter and track resolution

We emphasize that in all studies of the vertex detector performance the outer tracking detector is always taken into account; without it the accuracy of the vertex reconstruction is significantly worse. Target numbers for the impact parameter resolution were mentioned in Section 2: $a = 5\ \mu$m and $b = 15\ \mu$mGeV. The first parameter is mainly driven by the single-point resolution, the number and spacing of layers and the distance to the IP. Preliminary studies show that a value of $a = 5\ \mu$m should be achievable with 3 μm single-point resolution. Such a good point resolution would also help in the reduction of the occupancy due to background hits.

However, the requirement on the second parameter is more challenging. The value b is mainly driven by the amount of dead material and its distribution in relation to the active layers. To obtain $b = 15\ \mu$mGeV the material thickness should be approximately 0.1% of the radiation length (X_0) per single detection layer. Yet since the minimal beam pipe radius is fixed to 30 mm because of beamstrahlung, its thickness is fixed to ~ 0.6 mm $= 0.17\%\ X_0$ with current technology. Studies so far indicate that a value of $b = 20\ \mu$mGeV is more realistic including the beampipe, even with 0.1% X_0 per layer of the vertex detector.

For the reconstruction of the momentum of particles in the forward region the azimuthal angle of the hits on the disks is most important; the radial coordinate does not need to be measured with the same accuracy. Radial strips (with a small stereo angle) are therefore often considered for disk technology in the design of a new vertex detector. Yet with the dense background environment the disks in the CLIC vertex detector will be using pixelated technology to reduce the occupancy. Detailed optimization studies are underway and will be reported in a future publication [16].

5. Challenges for the technology R&D

Several technology domains encompass the development of a vertex detector. They can be classified in three areas: sensor technology, readout electronics and power delivery & dissipation. No single technology has been chosen yet for any of the domains; the requirement of no more than 0.1% radiation length per sensor layer is often the bottleneck.

The position resolution of a hit is required to be 3 μm. The time resolution has not been fixed yet, but should be of the order of 5 to 10 ns. Sensor technologies by themselves meet these demands, even the low mass requirement. Suitable readout electronics however needs further development. The time resolution and expected high occupancy can be dealt with by some technologies, yet these may exceed the maximum tolerated amount of material. Adapting their design to reduce the material thickness then touches on the power supply and dissipation: more dense electronics for the smaller pixels implies more heat per area which might imply more cooling material. R&D on cooling technology is therefore needed to keep this amount of material to a minimum.

For the power management the 0.02 seconds between bunch trains can be used. Even if all the information collected during one train is buffered in the readout electronics, the inter-train period can be used for readout *and* cooling. Assuming for example a readout of maximal 400 μs, a ratio of on- to off-time of approximately $1:50$ is possible. Electronics capable of power pulsing thus have a great advantage.

Detailed studies of the neutron flux from the spent beams at CLIC have not yet been performed. Preliminary studies indicate that the flux should be several orders of magnitude smaller than at the LHC, see [14], and radiation hardness is therefore thought not to be a crucial issue at CLIC. More detailed studies are underway, see also [17].

6. Conclusions

The consequences of the beamstrahlung at CLIC for the vertex detector are now under study. Especially in the forward region the density of particles from the background channels is high and a redesign of the vertex detector with respect to the ILC is necessary. A strawman design satisfying the requirements on the impact parameter resolution is under development. Both for the design and the development of the detector the biggest challenge lies in the low mass requirement.

In 2011 a Conceptual Design Report is to be published for the CLIC accelerator and its detectors. A complete detailed study of the vertex detector design will then be presented.

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