A Detector for the TESLA Linear Collider

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Abstract

A detector for e^+e^- experiments at linear colliders up to TeV energies is presented as it is discussed within the 2^{nd} ECFA/DESY Study on Physics and Detectors for a Linear Electron-Positron Collider. The expected detector performance matches well the requirements of the physics potential of such a collider, in particular it will allow to perform precision measurements at high luminosities.

1 Introduction

A high energy e^+e^- linear collider designed to operate in the c.m. energy range beyond the mass of the Z^0 and up to the TeV region is generally considered to be the next step for particle physics investigations. Such a collider represents a natural facility for the discovery of new particles and the precise determination of their properties as well as precision tests of the Standard Model. It would complement the physics potential of the Large Hadron Collider (LHC) presently under construction at CERN.

The design of a detector for an e^+e^- linear collider is driven by the physics potential as well as by the integrated luminosity and background conditions of such a machine. The physics potential of a linear collider has been studied in the past [1] and is subject of the ongoing 2^{nd} ECFA/DESY Study on Physics and Detectors for a Linear Electron-Positron Collider. A detailed account of the physics program is given by [2], it is in many aspects complementary to the program of the LHC. The properties of the top quark, the electroweak gauge bosons, the Higgs particle(s), supersymmetric or other new particles can be explored with high accuracy in a model independent way. These measurements will allow to cover the energy range above the existing machines up to the TeV region in a conclusive form and will elucidate the structure of matter at a fundamental level. In particular, essential elements of the Higgs mechanism can be established at a high luminosity e^+e^- collider. The main physics aims can be summarized as follows:

- Measurement of the mass of the top quark to an accuracy below 200 MeV;
- Measurement of the mass of the W boson to an accuracy of $\sim$15 MeV (by reconstruction of the final states) or $\sim$6 MeV (by dedicated running of the collider at the

threshold of W-pair production);

- Determination of the mass of the Higgs boson to an accuracy of ~50 MeV;
- Measurement of the Higgs coupling parameters at the % level;
- Measurement of the Higgs self-coupling to 20%;
- Large coverage of the parameter space of supersymmetric models and determination of SUSY-breaking mechanisms;
- Determination of triple gauge boson couplings to an accuracy of 10^{-3} to 10^{-4}.

In addition, many more interesting physics topics can be addressed at TESLA.

The TESLA collider [1, 3], utilising superconducting RF cavities for the main linac, is being developed by the TESLA collaboration, consisting of 36 institutes from 9 countries. At c.m. energies around 500 GeV it will operate with bunch trains of 2820 bunches, 337 ns apart, colliding 'head-on' with a frequency of 5Hz. A luminosity of a few times $10^{34}cm^{-2}s^{-1}$ is expected, a factor of ~4 higher than for colliders utilising normal conducting RF, assuming the same AC power and beam dimensions. For further details see [3]. The resulting backgrounds for the detector have been carefully studied and details are given in [4]. For example, at $\sqrt{s}$=500 GeV one expects, per bunch crossing, some 1000 photons within the tracking volume, around 60,000 pairs of e^+e^- and several TeV electromagnetic energy in the forward region within an angular region of 100 mrad with respect to the beamline. In addition, some 10^9 neutrons per cm^2 and year are expected.

The most essential design criteria and performance goals for the detector are driven by the physics program, the expected luminosity and the background conditions as described above and can be summarized as follows:

- Excellent vertex resolution for heavy flavour identification (e.g. for Higgs couplings);
- Tracking with accurate momentum determination and high redundancy (invariant and missing mass reconstruction);
- High granularity calorimeters for good energy-flow measurement (invariant and missing mass reconstruction);
- Full solid angle coverage and hermeticity down to polar angles of 20 mrad or smaller (missing energy measurement);
- Good lepton identification and $e-\pi$ separation;
- Large magnetic field of 3–4 T to achieve good momentum resoultion as well as to suppress low momentum beam induced background;
- Highly granular and low mass tracking system;
- Large tracking volume to detect long–lived particles;
- Good shielding against machine induced background and instrumentation at small angles ($\theta \leq 100$ mrad);
- Unbiased trigger or only software based trigger.

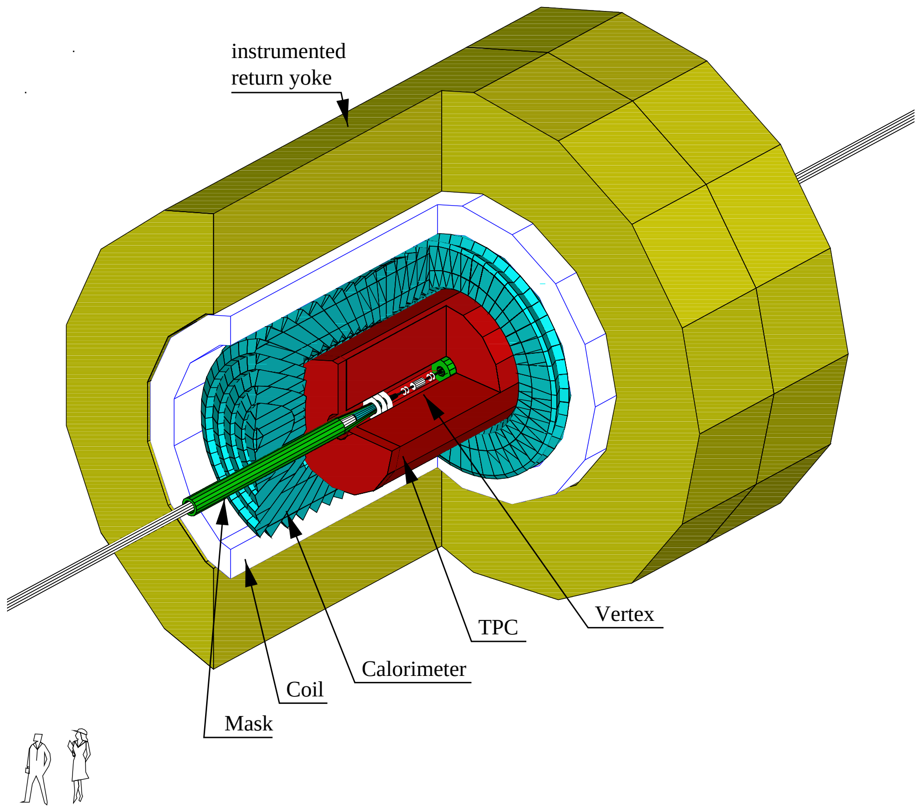

Figure 1: Schematic detector layout.

2 General Detector Concept

The general concept of a detector fulfilling the criteria mentioned above is described in this section as it is discussed within the *ECFA/DESY study*. More details about the detector and presently ongoing R&D can be found in [5]. The basic layout follows the well-proven concept of tracking in a magnetic field at inner radii and calorimetry at outer radii. A detector with a large solenoid and calorimetry inside the coil is favoured; the overall dimensions will be some 6m radius and 15m length. It allows to achieve best possible jet resolution and the detection of long-lived particles, which could e.g. exist in Gauge mediated SUSY breaking models. The detector layout is schematically shown in Fig. 1.

The tracking system consists of a multi-layer Silicon microvertex detector, a two-layer intermediate tracker followed by a large gaseous main tracking chamber and a hermetic, highly granular calorimeter, placed inside a superconducting solenoidal magnet. The magnet is surrounded by an instrumented return yoke, which serves as a muon detector. The polar angle region between $5°$ and $15°$ (not well covered by the TPC) is instrumented with a system of disk shaped tracking detectors to accurately measure the acollinearity of e^+e^- pairs and to improve the momentum resolution. The small angle region (20mrad$<\ \theta\ <$80mrad) is covered by an instrumented mask, which shields the inner detector against machine background and at the same time allows the detection of particles within the angular range indicated. In the following sections, some more details

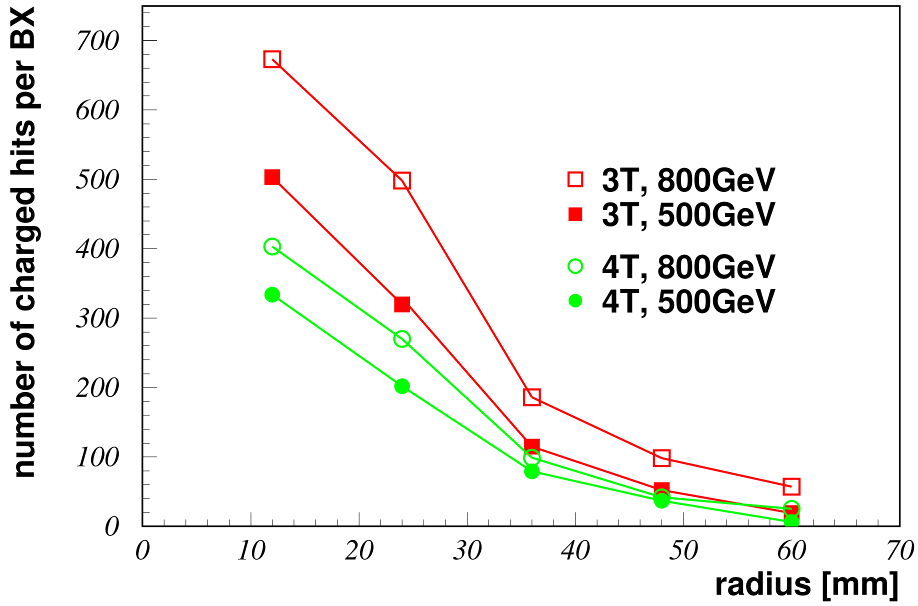

Figure 2: Number of charged hits per bunch crossing as a function of radius for $\sqrt{s}$=500 GeV and 800 GeV and magnetic fields of 3T and 4T, resp.

will be given concerning the different detector components.

3 Tracking

3.1 Magnet

The magnetic field plays two important roles: it bends charged particles for momentum measurement and it limits beam related background by imposing a cutoff in the transverse momentum of those e^+e^- pairs from beamstrahlung that enter the detector(see [4, 6]). In order to reduce the beam-pipe diameter, the aperture of the mask, and consequently reduce the background in the detector and enhance the physics capabilities, a field of at least 3T is necessary. With a higher field, the pair background in the vertex detector can be further reduced, as shown in Fig. 2. In addition, the momentum measurement with the tracking system is improved. A magnetic field strength of 3.5–4 T is presently favoured which is considered to be a reasonable compromise between high field, large volume and safe technology. The design of the magnet closely follows the design of the magnet for CMS [7], one of the large experiments presently under construction at LHC.

3.2 Vertex Detector

The requirements for the vertex detector are high granularity (for low occupancy despite large backgrounds and dense jet environment), low mass (for low multiple scattering), good spatial resolution (for precise vertex finding), and neutron tolerance (see above). Presently, multi(3 or 5)-layer devices are considered, consisting of CCDs or LHC-style active pixel sensors (APS). The magnetic field of 3.5–4 T will confine most of the e^+e^- pair background within the beampipe, allowing the vertex detector to be placed close to the beamline, with the first layer at a radius of 15mm. With a longitudinal extension of the first layer of z=±5cm the occupancy is expected to be at or below the permille level due to the high granularity of the device, whereas the solid angle coverage of the vertex detector will be as high as 96%. More details about the different vertex detector options under consideration as well as the excellent physics capabilities expected with the proposed device can be found in [8].

3.3 Central Tracker

A large-volume time projection chamber (TPC) has been chosen as the main tracking device because it offers an unmatched number of space points resulting in simple and efficient pattern recognition of complex events, good momentum resolution and particle identification. At the same time it represents little dead material, limiting the effects from multiple scattering or photon conversions. The design of the proposed TPC is based on the experience gained at LEP and elsewhere with large TPC systems (for more details see ref. [1]). In particular, the parameters of the TPC in use at ALEPH [9] were scaled to meet the more stringent requirements at TESLA. The TPC will cover a cylindrical volume of radius 32cm to 170cm and length z=±250cm, represented by some 10^9 pixels in 3D. In the worst case, a hit occupancy in the TPC of less than 1% of all pixels from background events is expected. The momentum resolution as a function of the polar angle θ for the TPC only and the full tracking system (TPC, high resolution vertex detector and two layers of intermediate detector with a resolution of some $10 \mu m$) is shown in Fig. 3. For $\theta > 30°$ where the full number of TPC hits is available, the goal of $\sigma(p)/p^2 < 7 \times 10^{-5} GeV^{-1}$ for the momentum resolution is met. This resolution is required in order to measure the recoil mass spectrum of the di-muon system in the process $e^+e^- \rightarrow Z^0H^0 \rightarrow \mu^+\mu^-H^0$ with an accuracy given by the natural width of the Z^0 only.

In addition to space points the TPC will also provide some particle identification through the measurement of the energy loss dE/dx of the charged particle in the chamber gas. This information can be used to distinguish electrons from pions and kaons with more than 2σ separation and pions from kaons with up to 2σ separation up to momenta of ~20 GeV [10]. Examples of the use of particle identification in the TPC at TESLA can be found in [11].

Usually, TPC's are operated in a gated mode in order to suppress the feedback of positive ions created in the avalanche region back into the drift region where those ions could create field distortions. The present planning for the TESLA detector calls for running without a dedicated hardware trigger (see section 6) and, therefore, requires the TPC to be sensitive for the whole bunch train of $950 \mu s$. In order to avoid positive ions drifting back into the drift region, a number of technologies are presently being investigated which replace the conventional grid of wires by other means like MSGC's [12], micro-megas gas chambers [13] or GEM foils [14]. More details can be found in [15]. Simulations have shown that a TPC should be able to operate in an ungated mode at TESLA, using one of the above mentioned technologies under study.

3.4 Forward Tracking

The polar angle region $15° > \theta > 5°$ is of special interest at e^+e^- linear colliders. Due to the effects from beamstrahlung and from initial state radiation, the effective c.m. energy

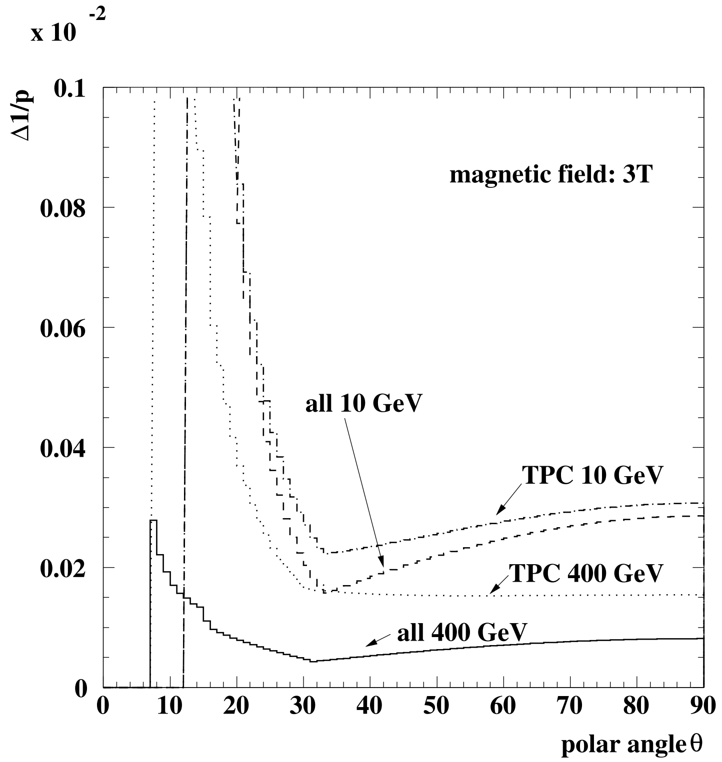

Figure 3: Expected momentum resolution as a function of the polar angle θ with a magnetic field of 3T.

has a distribution as indicated in Fig. 4. For many physics processes it is important to accurately measure this luminosity spectrum. This can be achieved through the measurement of the accolinearity of Bhabha events (e^+e^- pairs) which is most effective in the polar angle region indicated above. In addition, the number of hits per track in the TPC is reduced in that angular region and the otherwise excellent momentum resolution quickly degrades. In order to measure the accolinearity of Bhabha events to an accuracy of some $100\mu rad$ and to recover the momentum resolution, a system of seven disk shaped detectors together with a tracking detector between the TPC endplate and the endcap electromagnetic calorimeter has been introduced. The requirement on the spatial resolution of these devices is relatively modest, it is of the order of $50\mu m$.

4 Calorimetry

Calorimeters are essential for measuring energy and missing energy, the characteristic signature of supersymmetric particles and neutrinos, as well as the direction of photons, and, together with the tracking system, for measuring jet energies and jet directions. In order to achieve the best possible energy resolution, both parts of the calorimeter, the electromagnetic and the hadronic one, will be placed inside the coil. They should represent roughly 25 radiation lengths and 5-6 interaction lengths, respectively. Several options are presently discussed: A'tile' calorimeter based on a sandwich of absorber and scintillator with wavelength-shifting fibres coupled to clear fibres which take the signal out parallel to the beam line; the same materials but in a 'Shashlik' configuration, i.e. fibres running radially; and a 'high-granularity' calorimeter based on highly segmented

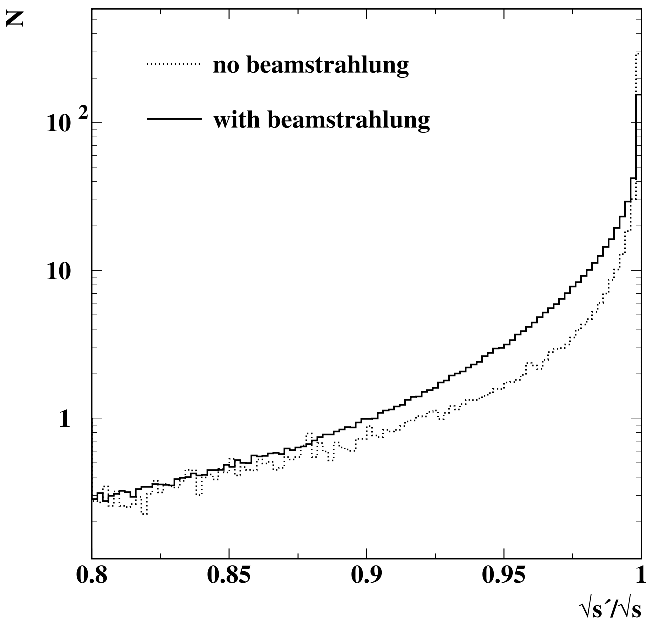

Figure 4: Distribution of the expected luminosity as a function of the effective c.m. energy $\sqrt{s'}/\sqrt{s}$ (luminosity spectrum).

SiW modules for the electromagnetic part. The latter option would allow a transverse segmentation as fine as $1 \times 1 cm^2$ compared to more than $3 \times 3 cm^2$ for the other two options. The longitudinal segmentation could be as high as the number of layers in the tile and SiW version and would be rather rather coarse in the Shaslik version. All three options are comparable in their energy resolutions of approximately $10\%/\sqrt{E}$ and $40\%/\sqrt{E}$ for the electromagnetic and hadronic part, respectively. The high granularity option would allow excellent accuracy for measuring photon directions, important e.g. for supersymmetric models with long-lived neutral particles, decaying into photons (GMSB-models). More details on calorimetry can be found in [16].

5 Small Angle Region

The small angle polar region below $\theta = 5°$ is of crucial importance to shield the inner detectors from machine induced background and at the same time allow a measurement of the energy deposited in that region in interesting physics events. Hermiticity down to as small as possible polar angles is important for processes with small visible energy and small visible transverse momentum (momentum component transverse to the beam direction). An example for such processes is the pair production of SUSY particles like $e^+e^- \rightarrow \tilde{\mu}^+\tilde{\mu}^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0\mu^+\mu^-$. A small mass difference between the $\tilde{\mu}$ and the stable lightest supersymmetric particle $\tilde{\chi}_1^0$ which escapes detection will result in events with small visible energy and transverse momentum. The two-photon reaction $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ constitutes the main background to the SUSY process with several orders of magnitude larger cross-section. If the electrons of the two-photon reaction escape detection, the

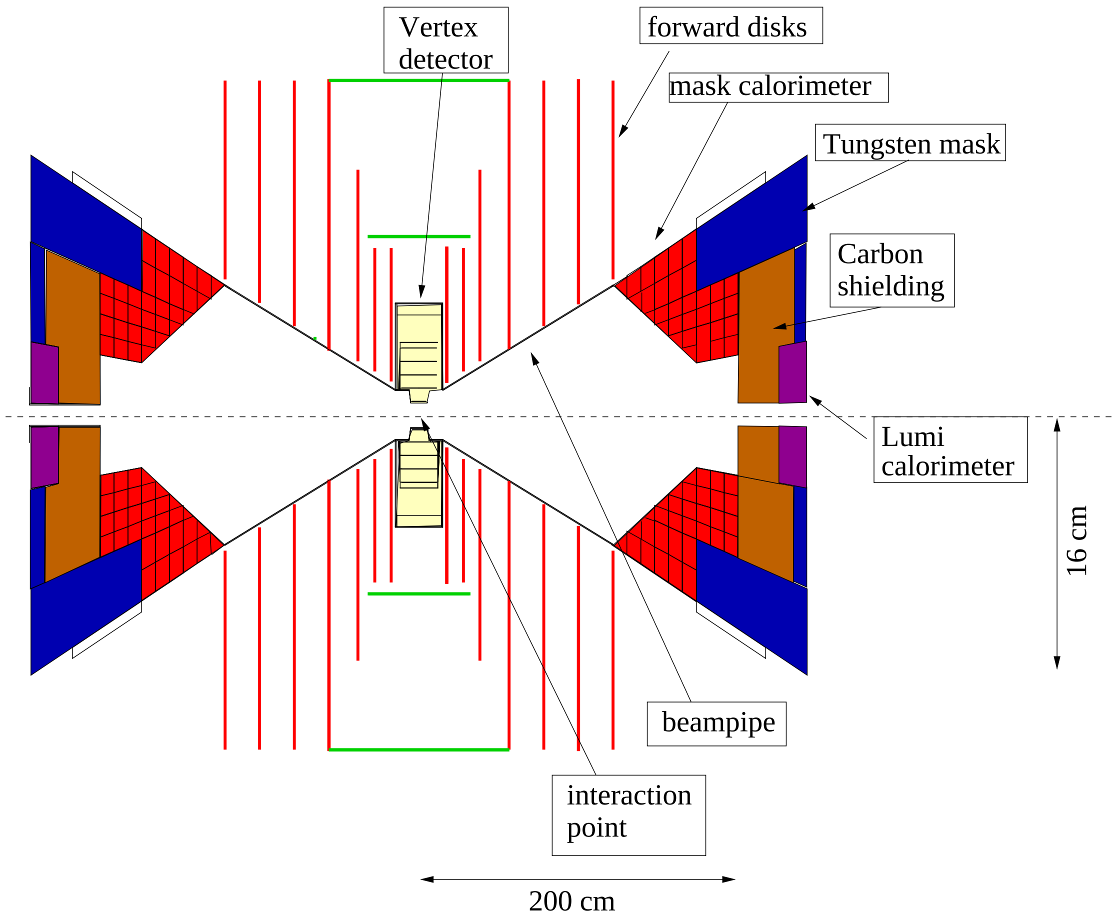

Figure 5: Schematic layout of the instrumented mask.

measurement of the production of SUSY particles with small mass differences is not possible. Therefore, an instrumented mask down to small polar angles is vital for the detection of such processes. Fig. 5 shows the present proposal for the layout of the mask which will allow to efficiently shield the detector from machine induced background and detect at least electromagnetically showering particles (electrons and photons) down to polar angles of (20-25)mrad. The possibility of detecting even minimum ionising particles is under investigation as is the technology for the instrumentation of the mask.

6 Trigger

As discussed in the introduction, at TESLA bunch trains consisting of 2820 bunches spaced by 337ns will collide with a frequency of 5Hz. With the design luminosity of a few times $10^{34} cm^{-2} s^{-1}$ the expected rate of physics events is of the order of a few Hz. This operation condition calls for a deadtime-free data taking within 1ms at a repetition rate of 5Hz. Rather than using a conventional multi-level trigger scheme with a purely hardware based first level, a single-level software selection running on commodity hardware is proposed. All detector signals are digitized and stored in buffers for each collision prior to event building through a fast network. All bunches are then analysed in a processor farm and classified in various streams from interesting physics events to background, monitoring, and calibration events. The clear advantages of this scheme are a deadtime-free readout, excellent 'trigger' flexibility, since the full event information will be available for the decision finding process, and very good scalability. This 'trigger' strategy is especially attractive for some classes of physics processes with unfavourable topologies like few low momentum tracks, little deposited energy, and for the search for rare or yet unknown classes of events.

According to first estimates, the event building process will have to cope with one to two Gigabyte of data per second, given the present granularity of the detector. In view of the corresponding values anticipated at LHC experiments, this is not an unrealistic goal to be achieved.

7 Summary

Within the 2^{nd} ECFA/DESY study, a detector is being designed which surpasses the already excellent performance of the LEP/SLC detectors and which has been considerably improved with respect to the detector proposed in the framework of the 1^{st} study. The main features of the detector are a solenoidal magnet with a field of 3.5-4T with the tracking system and the electromagnetic and hadronic calorimeter placed inside the coil. The tracking system consists of a high precision Silicon vertex detector, with the first layer placed at a radius of 15mm, followed by a two-layer intermediate tracker and a large volume TPC. This system will deliver a momentum resolution of a few times $10^{-5} GeV^{-1}$. The calorimeters will have high granularity and, therefore, will provide excellent jet angular and energy resolution. The detector will be complemented by a system of forward disks and an instrumented mask thereby providing hermeticity down to a polar angle of 20mrad and an angular resolution of $100\mu rad$ down to some $5°$. The magnet return yoke will be instrumented for muon identification. No hardware trigger will be implemented, all data will be stored and presented to a purely software based 'trigger' thus allowing a deadtime-free running combined with the best possible efficiency and flexibility for event selection.

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References

[1] *Conceptual Design of a 500 GeV e^+e^- Linear Collider with integrated X-ray Laser Facility*, Vol. *I&II*, DESY 1997-048, ECFA 1997-182, Editors R. Brinkmann, G. Materlik, J. Rossbach, A. Wagner, and references therein.

[2] P. Zerwas, these proceedings.

[3] R. Brinkmann, these proceedings.

[4] D. Schulte, these proceedings.

[5] *Proceedings of the International Workshop on Linear Colliders (LCWS99)* at Sitges, May 1999.

[6] C. Hensel, *Beam induced background at a TESLA detector*, LC electronic note, LC-DET-2000-001-TESLA,
(see http://www.desy.de/lcnotes/LCnotes_welcome.html).

[7] CMS Collaboration, *The Magnet Project Technical Design Report*, CERN/LHCC 97-10, May 1997.

[8] M. Battaglia, these proceedings.

[9] ALEPH coll., D. Decamp et al., Nucl. Instr. Meth. **A294**(1990)121,
ALEPH coll., D. Decamp et al., Nucl. Instr. Meth. **A360**(1995)481.

[10] M. Hauschild, private communication.

[11] R. Hawkings, *CP violation studies in b decays at the TESLA Z factory*, LC electronic note, LC-PHSM-1999-001-TESLA,
(see http://www.desy.de/lcnotes/LCnotes_welcome.html).

[12] A. Oed, Nucl. Instr. Meth. **A263**(1988)351,
A. Oed, Nucl. Instr. Meth. **A367**(1995)34,
W. G. Goy et al., Nucl. Instr. Meth. **A374**(1996)144.

[13] P. Colas, contribution to DESY 97-123E,
Y. Giomataris et al., Nucl. Instr. Meth. **A376**(1996)29.

[14] F. Sauli, Nucl. Instr. Meth. **A386**(1997)531,
F. Sauli and A. Sharma, CERN EP/99-69.

[15] T. Behnke, in: *Proceedings of the International Workshop on Linear Colliders (LCWS99)* at Sitges, May 1999.

[16] L. Jönsson, these proceedings.