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# DETECTOR STUDIES FOR TESLA*

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European preparations for building a detector for the $e^+e^-$ physics up to 1 TeV center-of-mass energies at the linear collider are described.

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## 1. Detector concept

### *1.1. Introduction*

A detector for $e^+e^-$ the linear collider (LC) is under conception. A preliminary version of it was prepared during the 1996 *ECFA/DESY Study on Physics and Detectors for the Linear Collider* [1] and resulted from one choice for subdetectors among many possibilities considered. This detector [2, 3] matches the requirements of the physics analyses up to the highest collider energies of $\sim 1$ TeV.

It was the starting point as so-called "reference detector" for the *2nd ECFA/DESY Study on Physics and Detectors for the Linear Collider* [4] which began last year (1998) and is still in progress. The performance of all subsystems is being reexamined in a "shakedown" of the reference detector in light of the upgraded design of the TESLA Linear Collider which will deliver an order of magnitude greater luminosity than the first version. This new design will be denoted $hi\mathcal{L}$ TESLA in the following. Also detector R&D projects will be launched in order to better decide which subdetectors to build.

This R&D will be carried out in cooperation with the American and Asian regions which also have linear collider studies [5] under way for their machines, NLC and JLC respectively. This will establish a basis for a world

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collaboration to build a detector and do the physics at whichever LC machine gets approved. Here, the European version [2,3] will be referred to simply as the "TESLA Detector" although it is understood that it could do the physics at any of the machines.

### *1.2. Requirements*

The physics program of the linear collider has been the subject of intense investigation in the present [4] and past [6–21] workshops. The detector needs were evaluated [22–24] in some detail, but, quite globally, the physics for which the analysis power must be excellent ($\surd$) are:

| | DETECTOR | | | | |
|---|---|---|---|---|---|
| PHYSICS | Missing energy | Jet-jet reconstr. | Lepton resolution | b,c,$\tau$ vertexing | Forward direction |
| Higgs branching ratios | $\surd$ | $\surd$ | $\surd$ | $\surd$ | $\surd$ |
| Top threshold scan | $\surd$ | $\surd$ | | $\surd$ | $\surd$ |
| W-boson couplings | $\surd$ | $\surd$ | $\surd$ | | $\surd$ |
| $\tilde{\chi}_j^{\pm}\tilde{\chi}_i^0\tilde{\ell}\tilde{q}$ spectroscopy | $\surd$ | $\surd$ | $\surd$ | $\surd$ | |

Thus the detector must be really good. Some crucial points for designing the detector are:

- Good energy-flow measurement is ensured by high granularity in tracking and calorimeters for jet reconstruction and by good particle identification.
- Calorimeters are thus inside the coil with longitudinal granularity for software compensation and with a minimum of material in front of the electromagnetic calorimeter.
- Tracking with very accurate momentum determination is needed to measure *e.g.* the Higgs couplings.
- Excellent vertex resolution is needed for heavy flavour identification.
- The detector should be hermetic, with good measurement in the forward direction which gains on importance the higher the $e^+e^-$ $\sqrt{s}$.
- Very good lepton identification and e-$\pi$ separation are required.
- The trigger must be flexible to adapt to new physics.

The LEP detectors are presently gaining experience in handling multijet events at higher energies, and this has turned out to be one of the most difficult tasks at LEP2. This is the reason for the emphasis on very good jet and energy-flow resolution for the LC detector.

The second point above means putting a reasonable amount of the hadron calorimeter inside the coil guarantees that as many of the reaction products as possible are detected before the dead region starts. The reason for wanting this is simple, but not so easy to quantify: the more that is measured and the less that occurs in dead regions, the less dependent the measurements are on the Monte Carlo and the smaller are their systematic errors.

The performance goals are given in Table I and match the needs of the physics analysis and the technical feasibility. They result from the *2nd ECFA/DESY LC Study* [4] and are more ambitious than for the reference detector of the first study.

TABLE I

Detector performance goals

| | |
|---|---|
| Vertexing | $\delta(IP_{r\phi,z}) \leq 5\,\mu m \oplus \frac{10\,\mu m\,\mathrm{GeV/c}}{p \sin^{3/2}\theta}$ |
| Forward tracking | $\frac{\delta p}{p} < 20\,\%$, $\delta_\theta < 200\,\mu$rad<br>for 100–250 GeV particles<br>down to lowest polar angle $\theta$ |
| Tracking | $\frac{\delta p_t}{{p_t}^2} \leq 0.6 \cdot 10^{-4} (\frac{\mathrm{GeV}}{c})^{-1}$<br>Good particle identification ($dE/dx$) |
| Electromagnetic calorimeter | $\frac{\delta E}{E} \leq 0.10 \frac{1}{\sqrt{E}} \oplus 0.01$ ($E$ in GeV)<br>Granularity $\leq 0.9^\circ \times 0.9^\circ$,<br>$\geq 3$ samples in depth |
| Hadronic calorimeter | $\frac{\delta E}{E} \leq 0.50 \frac{1}{\sqrt{E}} \oplus 0.04$ ($E$ in GeV)<br>Granularity $\leq 2^\circ \times 2^\circ$,<br>$\geq 3$ samples in depth |
| Muon detector | Fe yoke instrumented as tail catcher<br>and muon tracker. Toroid or yoke momentum<br>analysis for forward muons,<br>$\frac{\delta p}{p} < 20\,\%$ for ($\theta < 15^\circ$) |
| Energy flow | $\frac{\delta E}{E} \simeq 0.3 \frac{1}{\sqrt{E}}$ ($E$ in GeV) |
| Hermetic coverage | $\lvert\cos\theta\rvert < 0.99$ |

## 2. Layout

The basic layout follows the well-proven concept of tracking in a magnetic field at inner radii and calorimetry at outer radii. Figure 1 shows a schematic cross section through the version arising from the first *ECFA/DESY Study* [1]. Figure 2 gives details of the inner region.

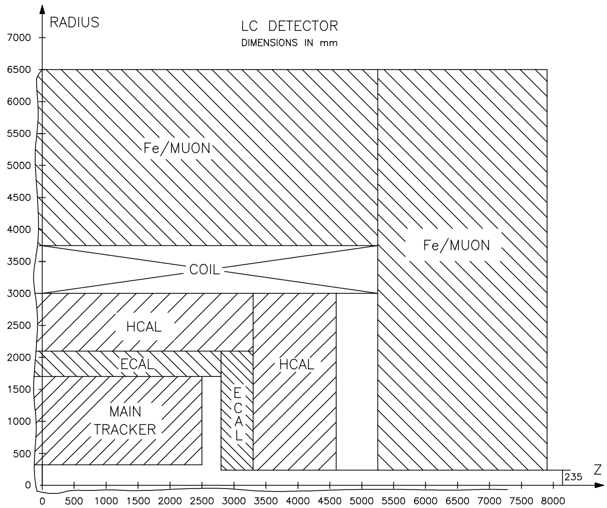


Fig. 1. Schematical layout of one quadrant of the LC Detector

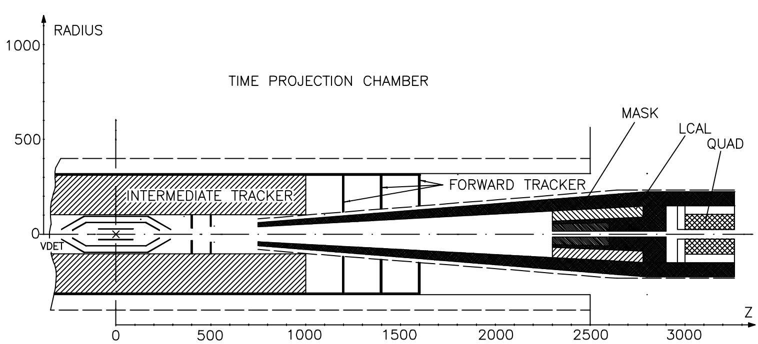


Fig. 2. Schematic layout of the inner region of the detector

### *2.1. Subdetector alternatives*

Table II shows subdetector techniques being studied within the ECFA/ DESY series. This table is being formed stage and thus not complete, and apologies to those doing R&D who are not yet in the list.

TABLE II

Techniques being considered for the LC detector

| Subdetector | Technique | Labs involved |
|---|---|---|
| **Barrel** | | |
| Vertex detector | • CCD<br><br><br><br>• APS | • *LCFI Group:* Brunel, Glasgow, Lancaster, Liverpool, Oxford, RAL, U.Oregon, UCSB<br>• CERN, Cracow, Helsinki, Milano |
| Intermediate tracker | • Honeycomb straw tubes<br>• Scintillating fibres<br>• GEM<br><br>• Si-Strip | • Aachen<br>• Zeuthen, ETH Zürich<br>• Aachen, Brussels, CERN,Helsinki<br>• |
| Main tracker TPC | • Gas studies<br>• Wire chamber readout<br>• GEM readout<br><br>• Micromegas readout | • CERN,Cracow<br>• LBL,MPI-Munich<br>• CERN,DESY,LBL, MPI-Munich<br>• Saclay |
| Presampler | • Scintillating fibers | • DESY/IfH-Zeuthen |
| $\mathcal{E}$cal, $\mathcal{H}$cal | • Pb,Cu-scintillator Shashlik<br><br><br>• Shaslik,crystals,glasses<br><br><br>• Heavy liquid<br>• Silicon/Tungsten | • *Caleido Coll.:* Bologna, CERN,Milano,Padova, Protvino,Serpukov<br>• *Intas Coll.:* DESY, Lebedev(Moscow),Lund, INP-Tashkent<br>• UCSC<br>• Ecole Polytechnique |
| Tailcatcher, muon identifier | • Resistive plate chambers | • Bologna,Frascati |
| **Forward** | | |
| Forward tracking discs | • Silicon strip | • |
| Forward muon tracker | • Tracking in B-field, yoke<br>• Toroids with honeycomb tubes | • Bologna,Frascati<br>• Bologna,Frascati |
| $\mathcal{L}$cal | • Quartz fibre<br>• Parallel plate<br>• Liquid scintillator<br>• Heavy-gas/GEM | • Frascati<br>• Frascati<br>• Frascati<br>• Protvino |
| Instrumented mask | • Quartz fibre<br>• Parallel plate<br>• Liquid scintillator | • Frascati<br>• Frascati<br>• Frascati |

The different subdetectors chosen in the reference design are reviewed briefly in the following paragraphs and compared with the alternative being considered.

**Vertex detector**

Either Charged Coupled Devices (CCD) or Active Pixel Sensors (APS) could provide the performance required for a vertex detector. They are regarded as alternatives with R&D programmes continuing. The advantages of CCDs are their small pixel size ($20\,\mu\mathrm{m}^2$, compared with $50\,\mu\mathrm{m}^2$ for APSs) and their thinness ($30\,\mu$m of silicon with very light support structures, giving only $0.12\,\%X_0$ per layer, as compared with $0.8\,\%X_0$ for APS). The advantage of APSs is their robustness in the neutron background. Silicon strip detectors are shown not to be suitable in the vertex region because of occupancy problems with high multiplicity events and the photon background. The outer two layers of the vertex detector will taper down conically at 30° at the outer edge of the barrel to improve the forward tracking.

**Intermediate tracking region**

The intermediate tracker aids linking tracks from the main tracker to the vertex detector and can provide a fast track-trigger, which was the main reason for having a dedicated subdetector in the reference detector. Now the trigger is being redesigned (see Trigger below), as is also this inner region. Both straw tubes and scintillating fibers were investigated in the first study, and the straw-tube "honeycomb chamber" was chosen for the reference design as having the advantage of better intrinsic resolution and much less material ($0.23\,\%$ $X_0$ total compared with $1\,\%$ $X_0$ per layer for scintillating fibers). However now in the second study there is a preference for a chamber with 3-dimensional granularity in this region, a small TPC, a smaller inner radius of the large TPC, GEM detector or a layer of Si-strip are in the discussion. The latter would be either the **Intermediate Si-strip** layer itself forseen in the reference detector, which was included to provide a precise reference for aligning the vertex detector with the TPC and which improves the overall momentum resolution, or an additional such layer.

**Central tracker**

The TPC main tracker has a number of advantages over other techniques. It presents the minimum of material for the conversion of outgoing photons from beam-beam effects ($2.0\,\%$ $X_0$ for the inner field cage plus gas, compared with, for example, $10\,\%$ distributed over the whole volume for MSGCs). Its $z$ resolution is better than a jet chamber, and it can be gated to eliminate the distortion due to positive ions from the detection planes drifting into the detector volume. It is a cost-effective way of instrumenting a large sensitive volume with high tracking redundancy and 3-D granularity, gives reasonable particle identification via $dE/dx$, is more comfortable the larger the magnetic field and is easy to maintain; but it does require the magnetic field to be mapped to better that $10^{-3}$. A drawback is its 50 $\mu$s memory time which integrates over backgrounds from 100 bunch crossings in the case of $hi\mathcal{L}$ TESLA. This is being compensated for by striving for the highest possible granularity — a few $\times 10^9$ 3-D pixels in the gas volume. The various technigues possible under study for the readout planes are wire chambers, GEM and Micromegas.

**Electromagnetic calorimeter**

For the electromagnetic calorimeter, $\mathcal{E}$cal, the Pb-scintillator Shashlik technique was taken for the reference design since it gives better longitudinal granularity than a crystal calorimeter. The performance goal for the electromagnetic energy resolution $\lesssim 10\,\%/\sqrt{E}$ does not allow hardware compensation for the measurement of hadronic showers; good longitudinal granularity will enables this to be done in software. Crystals have better energy resolution but physics studies have shown that $\lesssim 10\,\%/\sqrt{E}$ will be sufficient for most physics. Included in the reference detector was a scintillating fiber presampler with thin layers of lead converter, which delivers precise coordinates for shower conversions and precise timing information. Liquid argon would involve cryostats which reduce the space for all inner tracking detectors and introduce dead space which compromises the hermeticity. Shashlik, crystals and glasses are still under study, and recently the design of a silicon-tungsten calorimeter started which looks very attractive.

**Hadron calorimeter**

Also for the hadron calorimeter, $\mathcal{H}$cal, a Shashlik approach was first chosen similar to that for the electromagnetic layer, but with copper as absorber. It would have the flexibility to optimize the granularity and sampling in depth to match the towers to those of the $\mathcal{E}$cal. There will be at least three or four interaction lengths of calorimeter within the coil at the equator, with more in the forward and backward towers. The alternative technologies for the $\mathcal{H}$cal are similar to those of $\mathcal{E}$cal discussed above.

**Instrumented iron**

The tail-catcher will use the iron return-yoke of the magnet to measure the leakage of energy from the back of the hadron calorimeter and escapes the coil. A powerful muon detector will result from sampling the muon tracks in the iron. Resistive plate chambers are likely to be cheaper and easier to build than limited streamer tubes for the same performance. Either technique can also provide fast triggering for cosmic ray events.

**Luminosity calorimeter and instrumented mask**

The luminosity calorimeter, $\mathcal{L}$cal, covering from about 30 to 55 (30 to 85) mrad for TESLA from the beam direction inside the tungsten shielding masks, has to measure high energy electron showers — in the presence of intense soft electromagnetic radiation from beam-beam pair production and beamsstrahlung. Solutions based on quartz fibers, parallel-plate chambers and liquid scintillator are being considered. The instrumentation of the tungsten mask using these technologies is also under investigation in order to obtain the best possible hermeticity. For this application quartz fibres are a good candidate since they are the most robust in a high background environment.

**Forward tracking**

A sequence of forward tracking detectors will be used to measure tracks close to the outer surface of the mask, especially muons and Bhabha electrons (for acollinearity measurement to give the luminosity spectrum). Discs of pixel or silicon-strip detectors will be inserted inside the intermediate tracking and inside the TPC inner cylinder (see Fig. 2). Also it is needed to measure the sign and the momentum of muons at small angles to the beam direction — *e.g.* in the study of $W^+W^-$ production or for the absolute c.m.s. energy determination. Toriods with tracking chambers were proposed for the reference detector. Recent studies indicate that a combination of the forward tracking detectors near the IP, outer tracking planes around the yoke and the return $B$-field of the detector magnet will yield the desired resolution, so that toriods are probably not needed.

**Magnet**

The magnetic field has two important rôles: 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. A field strength of $B = 3\,\mathrm{T}$ was chosen for the reference detector as a reasonable compromise between high field, large volume and safe technology. The 4T technology is now well advanced for CMS, so that this is being reconsidered for the TESLA detector. The dimensions of the coil are determined by the need to have good momentum resolution and the decision to have the electromagnetic calorimeter and part of the hadronic calorimetry inside the coil. This leads to the choice of an internal coil diameter of 6 m. In order to provide good tracking down to $|\cos\theta| = 0.99$, good field homogeneity is required for the TPC in order to reduce $E \times B$ distortions on the electron drift. Thus the length of the magnet was chosen to be 9.2 m. With these dimensions the last quadrupoles are inside the coil and since they are superconducting at TESLA, they have a maximum field allowed at the conductor, which was 3T in the first study. In the present *2nd ECFA/DESY LC Study* a new design of doublets based on $Nb_3Sn$ conductor, which can stand a much higher field, so that this would no longer be a hinderness for a 4T solenoid for the TESLA detector.

**DAQ and trigger**

At the design luminosity the physics rate to be recorded was expected to be about 0.1 Hz for the first version and thus will be about 5 times higher for the $hi\mathcal{L}$ TESLA. Backgrounds expected to be rejected by the trigger include those arising from beam-beam effects, beam-gas interactions and cosmic rays. There must be flexibility for adjusting the trigger rate due to background to the needs of the experiment.

Table III shows DAQ rates for BaBar and LHC along with linear collider expectations from the first study. These allow a realistic design and a purely software trigger is now being proposed. Compared to the LHC requirements, the data acquisition for the experiment is not a critical issue.

TABLE III

Comparison of three triggering projects

| | BaBar | LHC | LC |
|---|---|---|---|
| Bunch crossing time | 4 ns | 25 ns | 4-708 ns |
| Level-1 accept rate | 2 kHz | 100 kHz | <0.1 kHz |
| Event building | 0.4 Gbit/s | 20-500 Gbit/s | 1 Gbit/s |
| Processing power | $10^3$ MIPS | $10^6$ MIPS | $10^5$ MIPS |

## *2.2. Backgrounds, rates*

The sources of background are beam-beam effects, synchrotron radiation and debris from the final quadrupoles, and muon backgrounds arising from upstream sources. The main backgrounds are due to beam–beam effects. Table IV gives an overview of some machine properties and related background rates.

Via the beam-beam interaction, each bunch crossing occurring within the time resolution of a subdetector may produce particles in addition to those of a real physics event triggered by a different bunch in the train. The row labeled "Minijet ev./100 ns, $p_T^{\min} = 3.2\,\mathrm{GeV/c}$" gives a measure of the probability of having stiff particles from underlying hadronic events in a good physics event for a typical subdetector with a timing resolution of 100 ns.

TABLE IV

Table of some machine properties and related backgrounds

| | Prev. TESLA | $hi\mathcal{L}$ TESLA | JLC/NLC |
|---|---|---|---|
| [Units in brackets] | 0.5 TeV | | |
| **Beam properties** | | | |
| $\mathcal{L}$ [$10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$] | 6 | 31 | 7 |
| Trains/s | 5 | 5 | 120 |
| Bunches/train | 1130 | 2820 | 95 |
| Interbunch spacing | 708 ns | 337 ns | 2.8 ns |
| $\mathrm{N}_{\mathrm{e}^\pm}$ per bunch [$10^{10}$] | 3.6 | 2.0 | 0.95 |
| $\mathrm{N}_{\mathrm{beamstr.}\gamma}$ per $\mathrm{e}^\pm$ | 2.0 | 1.6 | 1.1 |
| $\delta_B$ [%] | 2.5 | 2.7 | 3.8 |
| **Backgrounds/bunch** | | | |
| $\mathrm{N}_{\mathrm{beamstr.e}^\pm}$/bunch crossing $\theta > 150\,\mathrm{mrad}$, $p_t > 20\,\mathrm{MeV}/c$ | 31 | 45 | 10 |
| Hadr.ev./bunch $E_{\gamma\gamma-\mathrm{c.m.s.}} \geq 5\,GeV$ | 0.13 | 0.23 | 0.08 |
| Minijet ev./bunch [$10^{-2}$] $p_T^{\mathrm{min}} = 3.2\,\mathrm{GeV/c}$ | 0.30 | 0.59 | 0.20 |
| **Backgrounds/100 ns** | | | |
| $\mathrm{N}_{\mathrm{beamstr.e}^\pm}$/100 ns $\theta > 150\,\mathrm{mrad}$, $p_t > 20\,\mathrm{MeV}/c$ | 31 | 45 | 357 |
| Minijet ev./100 ns, $p_T^{\mathrm{min}} = 3.2\,\mathrm{GeV/c}$ | 0.003 | 0.006 | 0.07 |
| Hadr.ev./100ns $E_{\gamma\gamma-\mathrm{c.m.s.}} \geq 5\,\mathrm{GeV}$ | 0.13 | 0.23 | 2.8 |
| **Physics events per hour** | | | |
| Bhabha | 3200 | 17600 | 3700 |
| $W^+W^-$ | 140 | 770 | 160 |
| $\mathrm{t\bar{t}}$ | 15 | 82 | 18 |
| $\mathrm{ZH_{SM}}$ | 1.2 | 7 | 1.4 |

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