Linear Collider Detector R&D

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1 Introduction

There is now global consensus that the next accelerator project in particle physics needs to be an electron-positron linear collider (LC) with an energy range between $\sqrt{s} = M_Z$ and about 1 TeV. The physics goals of the linear collider require advances now in the detector technology to optimize the outcome of the experiments which will be characterized by small cross sections.

Several requirements exceed the current state of the art in detectors (see below). Physics and detector studies are ongoing in Asia [1, 2], Europe [3, 4, 5] and North America [6, 7], and are co-operating within a World-Wide Study [8]. The co-chairs of the world-wide study [9] have suggested the compilation of this note to describe the detector R&D required for the timely construction of a detector with the required performance, to list the R&D efforts presently pursued and to point out the areas where efforts are missing or inadequately covered.

The purpose of this compilation is to help organise the R&D efforts more globally and to facilitate and foster interregional collaborations. This note is not meant to be prescriptive or exhaustive. There might well be areas of R&D which are useful to be exploited but which are not mentioned here. We also expect and encourage ideas on novel detector techniques. Explicitly included in considerations here are software developments in the context of the specific R&D efforts. We do not consider, however, generic software R&D which is mandatory but beyond the scope of this document.

In the past, much effort has been devoted to detector R&D for LHC experiments[10]. The principal challenges at the LHC are related to the high event rate and the high radiation levels associated with the luminosities and energies required to do physics. Both of these problems are dramatically reduced at the LC due to the lower beam energies and the falling e^+e^- point-like total cross section, in contrast to the higher beam energy and approximately energy-independent total cross section in pp collisions. The freedom from these problems at first sight might suggest that the LC detector requirements appear easily satisfied, but extensive studies since LCWS91[11] have motivated a very challenging detector which goes beyond the possibilities with current technology. The primary new requirements are unprecedented hermeticity, track-momentum resolution, jet-energy resolution and flavour identification for b and charm jets. The importance of these requirements is expanded upon in the next section. Briefly, the goals of the R&D programme include the following striking enhancements with respect to detectors at hadron colliders:

- 3–6 times closer inner vertex layer to the IP (higher vertexing precision),
- 30 times smaller vertex detector pixel sizes (higher track-angle precision),
- 30 times thinner vertex detector layers (reduced multiple scattering and photon conversions),
- 6 times less material in the tracker (reduced photon conversions),
- 10 times better track momentum resolution (better event selection purity) and
- 200 times higher granularity of the electromagnetic calorimeter (more powerful energy-flow procedures).

These advantages can be obtained since the readout speed and radiation hardness requirements at the LC are significantly relaxed relative to the LHC. But detector R&D is needed now to achieve the performance goals and to prepare for an optimal physics programme at the linear collider. Furthermore, with a detector R&D programme, one can expect new technologies to be developed, improving further the detector performance.

This document is structured as follows: In section 2 the required performance of the detector or detector parts is given, followed by a short description of the detector designs under consideration or proposed within the regional studies, together with their similarities and differences. Section 3 lists the R&D efforts presently underway for the individual detector parts. Finally, section 4 presents the areas where additional effort is known to be needed.

2 Detector Performance

2.1 Experimentation Aspects

The anticipated physics program at an e^+e^- linear collider encompasses the wide range of centre-of-mass energies $\sqrt{s}$ from M_Z to about 1 TeV and a large physics assortment from discovery to high precision measurements. Some of the most demanding physics topics for the detector design are:

- Track momentum and angular resolution.
  Very good track momentum resolution is required to study a number of physical processes. Examples include the model independent measurement of the Higgs boson mass and ZH couplings through the reaction $e^+e^- \rightarrow ZH \rightarrow \ell^+\ell^- X$ or the determination of new-particle masses in cascade processes as in supersymmetry (SUSY), $e^+e^- \rightarrow \tilde{\ell}^+\tilde{\ell}^- \rightarrow \ell^+\ell^-\chi^0\chi^0$ from the end-points of lepton spectra.

  Because a number of proposed new physics processes, e.g., chargino production, have strong t-channel contributions, it will be important to maintain good momentum resolution at very forward angles, to ensure reliable charge sign determination. In addition, the presence of beamsstrahlung demands a differential beam luminosity measurement when scanning over particle thresholds (e.g., W or top pair) to determine their masses and widths. The most accurate method known for differential luminosity measurement requires precisely measuring the kink angle between the outgoing electron and positron in low-angle Bhabha scattering[12].

- Vertex resolution.
  Flavor tagging derived from an excellent vertex detector is essential for many physics goals, including Higgs physics. For example, the determination of the couplings of the Higgs boson to fermions and bosons is dependent upon the performance of the vertex detector. Moreover, there are many physics processes which will be even more challenging. The typical events in the high energy regime will consist of multi-jet final states, and one will be obliged, due to small cross sections and hence small event samples, to extract the maximum possible information from these samples. For example, the high energy production of $t\bar{t}$ generally results in 6 jets, two being b flavoured and possibly another two being charm jets.

  If SUSY turns out to exist in nature, one may produce HA final states, where each of these heavy Higgs particles decays to $t\bar{t}$, doubling the complexity of the events. In these and many other crucially important processes, the capabilities of the vertex detector will be pushed to the limit. The measurement of vertex charge will take on great importance in reducing combinatorial backgrounds. Such physics scenarios drive the vertex detector design to be highly granular, with the best possible spatial resolution, extremely thin layers and an inner layer as close a possible to the interaction point.

- Energy-flow measurement.
  Many signatures from known processes and from new physics are expected to be found in jets of hadronic final states where intermediate states must be detected in cascade decays to identify these processes and to efficiently suppress backgrounds. The energy-flow technique combines the information from tracking and calorimetry to obtain an optimal estimate of the flow of jet particles and of the original four-momenta of the partons. Therefore excellent 3-D granularity is required also in the calorimetric detectors. Good particle identification and good coverage for long-lived particles are valuable additions for measuring as many

details as possible for each event.

- Hermeticity.
  Determination of missing energy requires a detector without dead zones and an opening along the beamline as small as possible. The detector parts at the smallest polar angles have to be radiation hard with short sampling and readout times to avoid event pile-up for calorimetric measurements in that environment which has fierce backgrounds due to beam-beam effects.

- Machine environment.
  There are several machine-related issues[13] which influence detector design and performance:

  - Background.
    The background conditions per bunch crossing (BX) for the various subdetector parts are to first order independent of the different machine designs. The effects arising from e^+e^- pairs associated with beamstrahlung at the interaction point (IP) give rise to neutron and photon flux in the tracking volume and calorimeter. These are of particular importance and constraints on the choice of technologies can be expected.
  - Bunch spacing.
    The bunch spacing is rather different between the cold and warm technologies and requires different sampling and readout times. Therefore the R&D needs to take these differences into account. For example these have an impact on the number of BX a subdetector sees and the amount of background to expect. The bunch spacing will also determine the hardware needed for stabilisation of the final quadrupole doublet, which could affect significantly the detector design and hermeticity.
  - Crossing angle.
    Because of bunch spacing the crossing angle of the two beams are different for the warm (8–20 mrad) and cold (head-on) technologies, so that the backgrounds expected at the inner subdetectors will have implications for the R&D requirements.

2.2 Detector Goals

The generic e^+e^- detector is composed of a tracking system (vertex, main and possibly intermediate tracker), calorimeter (electromagnetic and hadronic), coil, instrumented flux return yoke, and forward detectors. Some main performance goals resulting from the past three years of World-Wide Studies[8, 5] are

- for vertexing $\delta(IP_{r\phi,z}) \leq 5\,\mu\mathrm{m} \oplus \frac{10\,\mu\mathrm{m\,GeV/c}}{p\sin^{3/2}\theta}$,

- for central tracking $\delta(\frac{1}{p_t}) \leq 5 \times 10^{-5}(\mathrm{GeV/c})^{-1}$ with systematic alignment uncertainties $\leq 10\,\mu$m in the barrel region,

- for forward tracking $\delta(\frac{1}{p_t}) \leq 3\times10^{-4}(\mathrm{GeV/c})^{-1}$ and $\delta\theta \leq 2\times10^{-5}\mathrm{rad}$ for $|\cos\theta| \leq 0.99$,

- for energy-flow $\frac{\delta E}{E} \simeq 0.30 \frac{1}{\sqrt{E(\mathrm{GeV})}}$ meaning both electromagnetic and hadron calorimetry must be inside the coil and

- for hermeticity excellent forward coverage with the beam pipe as the only (~ 10 mrad) hole in the 4π acceptance.

- Finally to be robust against backgrounds, there should be minimal material inside the ECAL, finest granularity in all subdetectors and a large (> 3T) $\vec{B}$-field are envisaged.

3 R&D Presently Performed

This section contains a compendium of different technologies presently under consideration for a detector at the linear collider together with the R&D issues and the projects which are ongoing or being planned at the moment. No discussion of the different overall designs nor their respective advantages or disadvantages is given. An attempt is made to be as complete as possible and to indicate areas where information is still missing.

3.1 Tracking System

All tracking-system designs under consideration include a pixelated vertex detector that closely surrounds the interaction point for accurate measurement of charged particle impact parameters. Accurate momentum measurement is provided by either a large-volume gas drift chamber (axial/stereo wires or time projection chamber) or additional silicon tracking layers (silicon drift detector or microstrips) immersed in axial magnetic fields of magnitude ≥ 3.0 T. Most designs also include a dedicated system of forward-tracking silicon disks at low angles. For the gas chamber barrel trackers, additional special silicon, straw chamber or scintillating fiber layers are also under consideration for improving pattern recognition, momentum resolution, or timing precision.

3.1.1 Vertex Detector

Accelerator backgrounds dictate the minimum radius at which the first layer of the vertex detector can be placed. The two backgrounds of most concern are Bethe-Heitler electron-positron pairs created by radiation from the incident beams and the neutron backsplash from masks downstream of the interaction point. The first can create unacceptable occupancy and is directly affected by the strength of the detector's solenoidal field. The second is a source of radiation damage, with a nominal expected annual rate of $3 \times 10^8/\mathrm{cm}^2$. Uncertainties in background calculations are large, however, making it desirable to be able to withstand much higher rates without significant performance deterioration.

Traditionally there has been a tradeoff in pixelated detectors among intrinsic spatial resolution, readout speed, radiation hardness, and material thickness (which degrades impact parameter resolution at low momenta). Readout speed is most critical in the TESLA accelerator design where integrated particle occupancy in the first vertex detector layer over a full bunch train (950 μs) would approach 4%. In the following, brief descriptions are given of ongoing detector R&D related to a variety of pixel technologies.

Charged Coupled Devices (CCDs)
The CCD vertex subdetector[15] of the SLD detector has shown the power of CCD technology in a low-duty-cycle accelerator such as the LC. CCDs offer demonstrated intrinsic spatial resolution below 5 μm and potentially very low material thickness since active regions are of $\mathcal{O}(20\mu\mathrm{m})^3$ with readout proceeding directly through the bulk. Their disadvantages include slow readout speed and modest radiation hardness. Three collaborations are actively pursuing R&D to develop CCD technology for a linear collider detector. The LCFI (Linear Collider Flavour Identification) Collaboration[16, 17], consisting of six U.K. institutes (Bristol, Glasgow, Lancaster, Liverpool, Oxford, RAL); a U.S. collaboration[18] (Oregon, Yale); and a Japanese collaboration (see[1]) (KEK, Niigata, Tohoku, Saga, Toyama) are working in parallel on some or all of the following issues:

- Thinning the silicon bulk to a minimum with a goal of $\sim$0.1%X_0/layer
- Prototyping a mechanical support based on tension ("stretched CCDs")
- Manufacturing radiation-harder detectors and development of techniques for coping with radiation (e.g., charge injection to fill traps)
- Developing higher readout clock speed, parallel-column readout and greater integration of readout electronics
- Developing CCD operation at near room temperature (Japanese groups)

Active Pixel Sensors
Two types of Active Pixel Sensors (APS) devices are receiving scrutiny as alternatives to CCD vertex detectors. Hybrid devices (HAPS)[19, 20] are being studied by a European collaboration (CERN, Helsinki, INFN, Krakow, Warsaw) where work is underway to reduce material thickness and improve spatial resolution through smaller pitch and interleaved readout exploiting capacitive charge division, by analogy with the use of this procedure for microstrip detectors.

Monolithic Active Pixel Sensors (MAPS)[21, 22], an approach based on CMOS technology, offers intrinsic spatial resolution comparable to CCDs with the advantage of avoiding charge transfer through the bulk. The Strasbourg and RAL groups are developing this technology with the goals of producing large devices with the readout speed, noise performance and thin substrates required for the LC vertex detector.

Another new technology[23] involves the DEPFET (depleted FET) concept pioneered by the MPI-Munich group. In this device, the charge storage takes place in a buried channel below the conducting layer of a surface-channel MOSFET. The standard (top) gate is held at fixed potential and the transistor current is modulated by the charge in the 'internal gate'. Readout is by off-detector CMOS circuits, presumably to be attached by bump-bonding as for the CCD option.

In general, the bump-bonding technology (pixel sensors to CMOS, CCDs to CMOS, CMOS to CCDs, CMOS to CMOS) is exploding commerially as well as for scientific sensors, and is opening up a number of exciting opportunities for the LC vertex detector.

3.1.2 Main Tracker

Excellent track reconstruction efficiency and momentum resolution are desirable over a large solid angle at the linear collider. Two distinct approaches are under consideration for the barrel tracking system, a large-volume gas drift chamber (axial/stereo wire or time projection) with many coarse measurements or a silicon tracker with a few precise measurements per track. Aside from the technical tradeoffs in designing within one of these approaches, there are global tradeoffs among them, pertaining to pattern recognition, robustness against background, material budget affecting multiple scattering, bunch discrimination via timing, and interface to calorimetry. Collaborative simulation work (Colorado, Michigan, Indiana, Santa Cruz, Wayne State) is pursued by the North American community to address these global issues[24]. Below is a summary of ongoing detector R&D for each of the barrel tracker technologies considered.

Jet Chamber

The Asian detector design includes an option for a large-volume drift chamber (radius 2.3 m, half-length 2.3 m) with axial and small-angle stereo wires. A long-term R&D program[1, 25] is well underway at KEK to address the following issues:

- Controlling / monitoring wire sag
- Maintaining uniform spatial resolution (85 μm) over tracking volume
- Maintaining good 2-track resolution (< 2 mm)
- Stable operation of stereo cells
- Gas gain saturation (affects dE/dx, 2-track separation)
- Lorentz angle effect on cell design
- Wire tension relaxation (Al wires)
- Gas mixture
- Coping with neutron backgrounds

Time Projection Chamber

The European and American detector designs include a large-volume time projection chamber (TPC) (radius 1.7 to 2 m, half-length ca. 2.5 m). A collaboration[26] of European (Aachen, DESY/Hamburg, Karlsruhe, Kraków, MPI-Munich, NIKHEF, Novosibirsk, Orsay/Saclay, Rostok) and North American Institutes (Carleton/Montreal, LBNL, MIT) has begun a comprehensive R&D program to address the following issues:

- Novel readout schemes to reduce the endplate thickness required to support conventional high-tension wire planes. Technologies considered at the moment are GEM[27] and MicroMEGAS[28], which should allow for good intrincic suppression of ion feedback. A method derived from silicon technology is also being studied. The wire-chamber alternative with high granularity was presented in the TESLA TDR[14] and is being further pursued as a backup to and benchmark for the new technologies.
- Readout channel reduction via optimized pad shaping/ganging with attention to 2-track and dE/dx resolution
- Optimized gas mixture (resolution vs fast drift speed, quenching with hydrocarbons vs reducing neutron-background effect), aging and implications for field cage.
- Electronics integration to cope with $O(10^6)$ or more readout pads and high-speed sampling (∼20 MHz or more) to exploit intrinsic longitudinal granularity, or (∼100 MHz or more) to exploit induced signals on neighboring pads
- Mechanical design to minimize material in field cages and endcaps, while providing adequate cooling for high-speed electronics
- Distortion correction techniques for coping with space charge buildup
- Calibration schemes (e.g., laser system, "z"-type[29] chamber at outer radius)
- Detailed technical simulations of readout designs with comparison to measurement of prototype devices

Silicon Tracker

The North American study groups are also considering in their simulations, in addition to the TPC described above, a 5-layer silicon barrel tracker of maximum outer radius 1.25 m and maximum half-length 1.67 m. Two different silicon technologies are under consideration: silicon drift detector and silicon microstrips, discussed below.

Si drift.

The Wayne State group[24, 30] has begun detailed simulations of a silicon drift detector design for the Linear Collider and advocates investigating the following issues in an R&D program:

- Development of thinner substrates and necessary mechanical support

- Improved spatial resolution (to better than 10μm in both dimensions)
- Increased drift length to reduce front end electronics (FEE) in the fiducial volume
- Lower mass FEE readout

Si microstrip.
A collaboration of UC-Santa Cruz and SLAC[24, 31] has begun detailed simulations of a silicon microstrip detector design and has proposed an R&D program to address the following issues:

- Development of thinner substrates and necessary mechanical support
- Development of very long ladders to reduce FEE in the detector volume and exploit reduced electronic noise with longer shaping time
- Detailed comparison of tradeoffs between long & short ladders, long & short shaping times, including tolerance to accelerator backgrounds
- Development of power-switching integrated readout electronics to exploit low duty-cycle of accelerator and reduce the necessary cooling infrastructure, with attention to stability.
- Study of Lorentz angle effects in strong magnetic fields
- Alternative p-side readout for double-sided sensitivity (e.g., stereo layer)
- Pulse height measurement for time-walk compensation and coarse dE/dx determination

It has been suggested that the mechanical rigidity requirements of the silicon trackers (drift or microstrips) could be eased by the use of an alignment monitoring system modelled on the ATLAS Detector's chirped interferometer scheme[32], allowing for less support material in the tracker's fiducial volume.

3.1.3 Forward and Intermediate Trackers

Most of the tracking system designs include a set of silicon annuli (discs) providing angular coverage to $|\cos\theta| \sim .99$. In the TESLA TDR design, the first three (of seven) disc layers from the interaction point are active pixel sensors; the rest are silicon microstrips, as are all of the annuli in the LC detector designs under study in North America. The design of the forward discs in the JLC detector design is open.

The UC-Santa Cruz / SLAC collaboration[31] working on barrel silicon microstrip R&D also plans simulations and prototype work on annuli development, including the necessary mechanical support structure.

Both of the European and North American TPC designs also include a barrel silicon layer at a radius just short of the inner radius of the TPC. The extra layer provides improved momentum resolution and provides improved pattern recognition to match tracks across the gap between the vertex detector and the gas chamber. The R&D being carried out or proposed by the LPNHE-Paris[33], Santa Cruz, SLAC, and Wayne State (silicon drift) groups for other silicon layers is expected to be relevant to this intermediate layer also.

The LPNHE-Paris group has also proposed[33] to insert large silicon annular planes behind the endcap of the European TPC and a large barrel layer beyond the outer radius of the TPC, in both cases between the tracking chamber and the electromagnetic calorimeter. The endcap tracking layer improves momentum resolution at forward angles, and the outer barrel layer offers a precise calibration point for the gas chamber, along with precise track extrapolation into the calorimeter. Given the sizes of these auxiliary tracking layers, lowering cost of manufacture will be important R&D goals.

A DESY group has proposed a superlayer of straw drift chambers behind the endcap of the European TPC, mainly to improve momentum resolution at lower angles[14, 12]. Technical R&D issues include spatial resolution, material thickness, timing for bunch tagging, and calorimeter splashback.

An Indiana group[24] is investigating the timing advantages of a superlayer of scintillating fibers in place or adjacent to the intermediate barrel silicon layer in the North American TPC option. R&D issues include timing precision and material thickness.

A collaboration of Hawaii, KEK and Tohoku has carried out simulations and has begun R&D on a dedicated "pair monitor"[34], based on active pixel sensor devices at very low angles near the final beam quadrupoles. The monitor would track the passage of Bethe-Heitler pairs, as a real-time beam diagnostic and as an independent measure of luminosity.

3.2 Calorimeter

3.2.1 General Description

In addition to the traditional functions of calorimeters - namely, measurement of individual electromagnetic and hadronic showers - a LC calorimeter system should provide the means of reconstructing jet 4-momenta through an energy flow algorithm (EFA). The EFAs rely on the measurement of momenta of charged particles in jets using the tracking system, the energy of photons and electrons using the electromagnetic calorimeter, and the energy of neutral hadrons (K_L^0, n) using both the electromagnetic and hadronic calorimeter. The algorithms depend critically on the ability of separating the different components among the energy deposits in the calorimeter. This requires high granularity (both longitudinal and transverse) in order to avoid double counting of energies and to assign appropriate weights, as demonstrated by H1; it will be verified by studies of EFAs for different types of calorimeters. The optimization of weights for electromagnetic and hadronic components may also be accomplished by hardware compensation. These studies are in progress as part of ongoing hardware projects or as explicit simulation studies.

The muon system must provide some calorimetry to detect leakage out of the calorimeter proper, and a forward system of calorimeters is needed to complete hermetic coverage and provide a luminosity measurement based on small angle Bhabha scattering.

3.2.2 R&D Projects

Electromagnetic Calorimeter (ECAL)

The ECAL is required to measure electromagnetic showers with excellent energy resolution, of the order of $10\%/\sqrt{E}$, and to be finely segmented to allow for the separation of the various components of jets. Several concepts are presently being evaluated:

a) *Silicon-Tungsten Sandwich Calorimeter.*

The SiW calorimeter provides the highest granularity ($\sim 1\mathrm{cm}^2$) combined with a very short Moliere Radius. Current areas of R&D [35, 14, 44] include production and quality control of Tungsten plates, design of the Silicon detectors, front-end readout chip and detector mechanics.

b) *Tile-Fibre calorimeter.*

The Tile-Fibre calorimeters presently under study allow less granularity starting with minimum tile sizes of around $4 \times 4\mathrm{cm}^2$. Several studies are going on world-wide [36, 14, 37, 38]. Particular emphasis lies on the study of tile sizes and the configuration of fibres. In order to supplement the granularity, shower-max detector layer(s) with a finer granularity, e.g. Silicon pad layer, may be added [36]. The use scintillators of different decay times for the front and back parts of the calorimeter is also under study by [36].

c) *Scintillator Strip Arrays.*

Scintillator strip arrays are being studied for a full calorimeter [39] as well as for a shower max detector [40, 41].

Hadron Calorimeter (HCAL)

All designs of hadron calorimeters presently under investigation are based on the concept of the sandwich calorimeter with either iron or lead plates as absorber. Several options for the active medium are being explored world-wide.

a) *Tile-Fibre calorimeters.*

One candidate for HCAL is the tile-fibre calorimeter where the segmentation is coarser than that of the ECAL. One criteria for the absorber material is the effective Moliere radius which includes the effect of the transverse shower spread in the scintillator gaps. Iron is advantageous in this respect. Lead has a shorter interaction length and is known to give hardware compensation at a lead/tile ratio of around 4mm/1mm. Investigations within the CALICE collaboration [35] include the mechanical design, study of tile sizes and fibre routing and, in particular, the read-out system. Hardware compensation is under investigation at KEK [42].

b) *Digital calorimeter.*

High granularity can be achieved with a so-called digital calorimeter where only the hit pattern is read out and no pulseheight information is being used. Candidates for the detecting medium can be RPCs (resistive plate chambers) [35, 46], GEMs (gas electron multiplier) [47], or wire chambers, each read out with pads of approximate size ~1cm^2. Studies of the active media, cross talk, gas mixtures, read-out systems, optimization of granularity, handling of additional pulseheight information are some of the many topics presently under investigation. Visual Light Photon Counters (VLPC) as detector element is being tested at [48].

Simulation Studies

Simulation studies related to specific calorimeter technologies and designs, and in particular to the development of Energy Flow Algorithms are under way at the institutes participating within all the above mentioned projects.
Additional simulation studies are also going on at several places [43, 44, 45].

3.3 Muon Detector

3.3.1 General Description

Although the main purpose of the LC muon detectors[49] is to identify muons by their penetration through Fe, the proposed muon detectors will also see significant deposits of hadronic energy since the calorimeters vary from 5.1 (NLC/SD), 5.4(TESLA), 6.7 (NLC/LD), to 7.5 (JLC) interaction lengths λ in depth. Thus, a properly instrumented muon system could also serve as backup calorimetry. Two candidate technologies, resistive plate chambers (RPCs)[50] or scintillation counter strips[51] are being studied, either of which may be used to instrument the gaps in the magnetic field Fe flux return yoke for the central solenoidal field. The R&D efforts for both of these systems overlap sufficiently to discuss them in parallel. If alternate calorimetry designs, such as LAr, are postulated, with a larger number of λ's, then conventional muon tracking systems, such as wire chambers, should be considered. The institutions involved in muon detector R&D studies are: INFN-Frascatti, Kobe Univ and other Asian institutes, Northern Illinois Univ, and Fermilab.

3.3.2 R&D Projects

- Muon System Mechanical Design
  The engineering for the muon Fe requires a detailed design that considers structural loads, construction techniques, installation of: Fe plates, detector planes, cables, etc. It is assumed that 4 to 5 cm gaps, between the 10 cm thick Fe plates that make up the return yoke, can be instrumented with RPCs, wire chambers or scintillation detectors.

- Monte Carlo and Tracking Studies
  Studies are needed to understand the effects of shower leakage on the energy-flow algorithms. Muon tracking software needs further development. Specific studies are needed for collisions at 0.8 to 1 TeV. The impact of background from decays of hadrons to muons in the beam lines and IR and hadron punch-through rates need to be determined and understood in the forward and central muon detectors, and accounted for in the muon system design.

- Muon Hardware
  Specifications for both RPC and scintillator based systems need further development in terms of dimensions, materials, construction plans and techniques, readout hardware and front-end electronics. Prototype detectors need to be built and tested. This, in turn, requires engineering to produce easily assembled, robust and reliable detectors and electronics. Cosmic ray testing (a test stand with data acquisition) will be required to provide feedback to muon system developers on questions of signal-to-noise, etc.

- Beam Tests
  Development of a high energy test beam will be essential to assess progress on prototype detectors and their electronics. In addition to measurements of detector efficiency, the energy calibration and resolution obtained for a prototype assembly of Fe plates and detectors in a hadronic beam of known energy, where jets can be observed, will be of significant importance. It is likely that other tracking detectors will need to participate in such tests.

3.4 Particle ID

The LC detector will surely make use of particle ID[52] via dE/dx, and if the main tracker is a gaseous TPC with many samples, as considered for TESLA, this will be valuable for physics. There remains the question as to whether a dedicated Cerenkov-based system should be considered, along the lines of the DELPHI RICH or the SLD CRID. The radial space requirement might be prohibitive, particularly in view of the greatly increased momentum range associated with the TeV-scale collisions. However, there remains some interest for two reasons. First, in the multi-jet environment of the most interesting new physics, jet energies are relatively low, and the mean particle momenta are of order 1 GeV/c. Secondly, the SLD experience showed the synergy between a vertex detector having topological capability (separation between primary, secondary and tertiary vertices) and hadron ID. A charged kaon emeging from an established charm vertex is a clear signature for a charm or anti-charm parent quark. Such information may be extremely valuable in reducing combinatorial background in SUSY or other new physics events. While it may not be possible to make space for a gaseous Cerenkov system, the DIRC technology pioneered by BaBar has been extremely successful, and may offer some potential for extending the range of K-pi separation in the LC detector. At least, this possibility seems worthy of detailed study, in conjunction with the full exploitation of the unprecedented performance of the expected vertex detector. The Colorado State group in the US has been actively investigating this capability.[43] So far the studies have been limited to simulation and reconstruction software development within the JAS framework.

3.5 Low-angle Detectors

There is much missing in this section.

Instrumented mask issues:
Calorimetric coverage, veto, lowest angle, crossing angle, background.

Luminosity detector projects known to date:
R&D is being planned by Colorado, DESY, UCLondon, Minsk and IHEP Moscow. A proposal is to be submitted to the DESY PRC[53] covering:
–diamond technology,
–crystal calorimetry with longitudinal segmentation,
–tungsten/gas-sampling and
–tungsten/Si-sampling.

3.6 Detectors for the $\gamma\gamma$ Collider

The final states that a $\gamma\gamma$ experiment[55] studies are almost identical to those in an e^+e^- experiment leading to similar detector requirements. There are a few impacts to the detector from the modifications necessary to accommodate the photon collider hardware. Also, the photon collisions themselves lead to some additional design constraints.

The laser pulses must be focused in the IR a few millimeters away from the IP. In the NLC design this leads to the inclusion of optics inside the beam pipe. Those optics add an additional 7cm of fused silica in the region from 35 - 100 milliradians. This will have an effect on low angle tracking, but should not generate additional backgrounds since it is outside the beam and e^+e^- pair background stay-clears.

For TESLA a storage cavity for the laser pulse has been proposed by the Max Born Institute. Such a cavity probably makes a crossing angle between the laser and the electron beam necessary. In this design all mirrors, i.e. material, can be placed outside the detector. As a drawback however, the dead region around the beampipe is somewhat increased. In both designs the much higher particle flux at low angles requires a redisign of the low angle taggers if physics requires them also in the $\gamma\gamma$ case.

The Compton backscattering creates a large energy spread in the initial electron beam. This leads to a much larger disruption during the beam-beam interaction. The outgoing beam pipe aperture must be enlarged to accommodate this and a field-free drift region to the dump is required. This will preclude post-IP diagnostics on the beam and will increase the amount of neutron radiation from the dump reaching the vertex detector. For the NLC standard beam dump configuration the flux will be 10^{11} neutrons/cm^2/year at the IP. Standard CCD vertex detector designs will not be able to handle this. Either rad-hard vertex detectors must be used or the beam dump must be re-engineered to reduce the neutron flux. LHC vertex detectors are within the range needed for this application.

The photon collider has a higher event rate than the e^+e^- experiment due to resolved photon events. The photon can fluctuate into a $q\overline{q}$ pair and thus has a hadronic component. It is expected that every event will have tracks in the barrel and endcap region from underlying resolved photon events. These will have an impact on b-tagging, jet resolution, and event energy balance. The TESLA bunch structure, with 337ns between bunches, should allow the detector to resolve individual crossings. The NLC, with 2.8ns spacing, will not allow individual bunch crossings to be resolved. The effect of these tracks on the detector performance needs to be well quantified before the time resolution requirements of the NLC detector can be specified.

In summary, the photon collider hardware modifications do not impose any detector constraints except for the SVX and the low angle taggers. Studies of the effect of resolved photon backgrounds on the reconstruction are needed before the detector requirements can be finalized.

3.6.1 Ongoing Work

- LLNL has done preliminary work on characterizing the resolved photon backgrounds on the jet energy resolution

- Further items should be included here.

4 Other Areas Needing Work

4.1 IP Instrumentation

Besides detector performance there are other topics to be investigated which are important for the physics studies at the LC. The following topics are therefore important and still being organized.[56]

- Beam energy determination.
  At high energies an accuracy of 10^{-4} is needed, which should be achievable by improving the beam spectrometer designs used at SLC and LEP. At lower energies (GigaZ) an accuracy of 10^{-5} is required which has to be developed in a dedicated R&D program.

- Polarisation measurement.
  Accurate measurement of polarisation below 10^{-3}, required in particular for GigaZ running, has to be studied.

- Quad stabilisation.
  This is a machine-detector-interface issue that is equally crucial for the detector. The bunch spacing will determine the hardware needed for quad stabilisation, which could affect significantly the design of the inner detectors.

4.2 Trigger

This secton is still missing.
All LC detector designs are based on a software trigger...[54]

5 Test Beams

The availability of test beams[57] will provide a rational way to make technical decisions for the LC detector. With the time scale of a running experiment ten years into the future we must maximize our development opportunities to see that proposed and planned detector elements will work as needed and advertised.

It is anticipated that new ideas and extensions to existing technologies will need to be tested with beam. Detector designs for high-resolution and high-speed CCDs, W-Si electromagnetic calorimetry, a TPC and other large volume tracking devices, will need to be tested with beam to make sure that designs can be reliably engineered into trouble-free detectors that can withstand beam conditions.

Test beam exposure will permit both software and calibration techniques to developed and tested along with the hardware. Data acquisition, controls and monitoring, and algorithms for handling single particles such as e's, mu's, pions, kaons, and objects such as secondary vertices, charm and bottom particles, jets and missing energy need to be tested. Crucial concepts such as energy-flow, identification of neutral hadrons and measurement of their energies, as well as unprecedented efficiency and purity in separating b and c tagged events need to be verified, Achieving results in test beams will assure a full cycle of design, perhaps several cycles, and implementation with regard to issues such as installation, power, cabling, cooling, survey and alignment, magnetic field tolerance, reliability, efficiency, and the determination of operating parameters such as voltage current, cooling, and humidity, etc.

All of this implies, in some important cases, the development of sophisticated test beam facilities at reasonably high energies. Such facilities exist at CERN, DESY, Fermilab, KEK and SLAC.

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