Linear Collider Detector R&D

August 28, 2002
http://blueox.uoregon.edu/~lc/randd.ps(pdf)

Editors
Jim Brau (jimbrau@faraday.uoregon.edu)
Chris Damerell (C.J.S.Damerell@rl.ac.uk)
Gene Fisk (hefisk@fnal.gov)
Yoshiaki Fujii (yoshiaki.fujii@kek.jp)
Rolf-Dieter Heuer (rheuer@mail.desy.de)
Hwanbae Park (sunshine@knu.ac.kr)
Keith Riles (kriles@umich.edu)
Ron Settles (settles@mppmu.mpg.de)
Hitoshi Yamamoto (yhitoshi@awa.tohoku.ac.jp)

Contents

1 Introduction

There is now global consensus in the high energy community that the next accelerator project in particle physics needs to be an electron-positron linear collider (LC) with an energy range from $\sqrt{s} = M_Z$ up to about 1 TeV. The physics goals of the LC will profit from advances now in the detector technology to optimize the outcome of the experiments. Improvements include reducing systematics to the lowest level in order to take advantage of the high luminosity for precision measurements and providing the best possible efficiency for rare processes with high jet multiplicity. This document describes the current status of efforts around the world to design detectors capable of meeting these demands.

Several requirements exceed the current state-of-the-art in detectors as will be seen below. To address this, 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 envisaged 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. Even as this note is being written, new efforts are being planned. Those which have not yet started are not included in this report, but will be listed on a web page [10] as they begin.

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 useful detector R&D ideas that have not yet been considered. 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.

Although a huge effort has been invested in detector development for the LHC program [11], with many benefits to other areas in high energy physics, there are nevertheless significant additional and different detector R&D challenges for the LC program. The principal challenges at the LHC are related to the high event rate and the high radiation levels associated with the pp energies and luminosities required to do physics with the parton component of the proton. Both of these problems are dramatically reduced at the LC where the 'bare partons', the electrons and positrons, are accelerated/collided directly, allowing competitive physics to be done with lower beam energies. This and the falling e^+e^- point-like total cross section are 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 performance is easily achieved, but extensive studies since LCWS91 [12] 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 issues 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 the LHC:

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

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, and indicates some areas where additional effort should be invested. Section 4 describes the test beam issues.

2 Detector Performance Requirements

2.1 Physics Considerations for Detector Design

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 broad range of physics goals, from discovery to high precision measurements. The implications for the detector has been the subject of many studies and reports [1]-[13] as explained in the introduction. Extracting from those studies some physics benchmarks that make stringent demands on the detector design are listed in the following for illustration.

- 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 $e^+e^- \to ZH \to \ell^+\ell^- X$ or the determination of new-particle masses in cascade processes as in supersymmetry (SUSY), $e^+e^- \to \tilde{\ell}^+\tilde{\ell}^- \to \ell^+\ell^-\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ from the end-points of lepton spectra.

Because a number of proposed new physics processes have strong t-channel contributions and because some standard model (SM) topologies (W^+W^-, ZZ, $t\bar{t}$) cover the full solid angle, it will be important to maintain good momentum resolution at very forward angles, which will ensure reliable charge sign determination and jet measurement. In addition, the presence of beamstrahlung demands a differential beam luminosity measurement when scanning over particle thresholds (*e.g.*, W^+W^-, $t\bar{t}$, SUSY thresholds) to determine their masses and widths. The most accurate method known for differential luminosity measurement requires precisely measuring the angle between the outgoing electron and positron in low-angle Bhabha scattering [14].

- Vertex resolution.
  Flavor tagging derived from an excellent vertex detector is essential for many physics goals, in particular Higgs physics. For example, the determination of the branching ratios of the Higgs to fermions and bosons is dependent upon the performance of the vertex detector. In particular, the measurement of the coupling to charm in the presence of a much larger bottom coupling challenges even the best vertex detector.

  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 $t\bar{t}$, $t\bar{t}H$ or ZZH generally results in at least 6 jets, two or more being b-flavored, and possibly another two being charm jets. Identifying these jet flavors will be valuable in reducing combinatorial and other backgrounds.

  The vertex detector will be important in other cases, where not all the heavy particles decay hadronically. For example, in high energy W production, important physics can be extracted from events in which one W decays leptonically and the other to $c\bar{s}$, by efficient and pure idenfitication of the charm jet.

  In SUSY models, there can be HA final states in which each of the heavy Higgs particles decays to $t\bar{t}$ giving rise to complex 12-jet 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 as 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; intermediate states must be detected in cascade decays to identify these processes and to efficiently suppress backgrounds. A key benchmark is the reconstruction of two jet decays of the W and the Z and the clean separation of these two gauge bosons. The energy-flow technique [1] combines the information from tracking and calorimetry to obtain the best possible 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.

- Hermeticity.
  Determination of missing energy requires a detector without dead zones and with minimal opening along the beamline. 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 high backgrounds due to beam-beam effects.

- Machine environment.
  There are several machine-related issues [16] 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 beamstrahlung and associated e^+e^- pairs at the interaction point (IP) give rise to neutron and photon fluxes in the tracking volume and calorimeter. These are of particular importance and constraints on the choice of technologies can be expected.
  - Bunch time structure.
    The bunch time structure is rather different between the cold and warm technologies and requires different sampling and readout times. Therefore the R&D should 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 time structure will also determine the hardware needed for stabilisation of the final quadrupole doublet, which could affect significantly the detector design and hermeticity. Furthermore, pile-up of $e^+e^- \to e^+e^- hadrons$ (two-photon) events will create different issues for the two technologies.
  - 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, the backgrounds

---

[1] In the past the term "energy flow" has been used for different techniques, so there is potential for confusion. Here the term refers to the ability to follow charged tracks into and inside the calorimeter to subtract charged-track deposits from the calorimeter signals before combining tracking and calorimetry information. See also Section 3.2.

expected at the inner subdetectors might be different and this 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 intermediate/forward tracker), calorimeter (electromagnetic and hadronic), coil, instrumented flux return yoke (or muon detector), and forward calorimeters. Some main performance goals resulting from the past three years of world-wide studies [1, 5, 6, 8] are

- for vertexing resolution: $\delta(IP_{r\phi,z}) \leq 5\,\mu\mathrm{m} \oplus \frac{10\,\mu\mathrm{m\,GeV/c}}{p\sin^{3/2}\theta}$,
- for central tracking resolution: $\delta(\frac{1}{p_t}) \leq 5 \times 10^{-5}(\mathrm{GeV/c})^{-1}$ with systematic alignment uncertainties $\leq 10\,\mu$m for a TPC or $\leq 1\,\mu$m for a silicon tracker in the barrel region,
- for forward tracking resolution: $\delta(\frac{1}{p_t}) \leq 3 \times 10^{-4}(\mathrm{GeV/c})^{-1}$ and $\delta\theta \leq 2 \times 10^{-5}$rad for $|\cos\theta| \leq 0.99$,
- for jet energy resolution: $\frac{\delta E}{E} \simeq 0.30\,\frac{1}{\sqrt{E(\mathrm{GeV})}}$ from energy flow, from which follows that both electromagnetic and hadron calorimetry be inside the coil,
- for hermeticity: excellent forward coverage with the beam pipe as the only small ($\lesssim$ 5-10 mrad) hole in the 4π acceptance, and
- for robustness in the presence of background: minimal material inside the electromagnetic calorimeter, fine granularity in all subdetectors and a strong ($\geq$ 3T) $\vec{B}$-field.

3 R&D Activities

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. Where specific details are given, they should be viewed as illustrative and not optimized.

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 $\geq$ 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-tube 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 dose of $\sim 10^9$ neutrons/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% without the improvements being planned. In the following, brief descriptions are given of ongoing detector R&D related to a variety of pixel technologies.

Charge Coupled Devices (CCDs)

The CCD vertex subdetector [17] 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 [18, 19], consisting of six U.K. institutes (Bristol, Lancaster, Liverpool, Oxford, Queen Mary-Univ. of London, RAL); a U.S. collaboration [20] (Oregon, Yale); and a Japanese collaboration [1] (KEK, Niigata, Tohoku, Toyama) are working in parallel on some or all of the following issues:

- thinning the silicon bulk to a minimum, with a goal of achieving a ladder thickness of $\sim 0.1\% X_0$,
- prototyping a mechanical support based on tension ("stretched CCDs"),
- manufacturing detectors which are more radiation hardened and developing 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, and
- developing CCD operation at near room temperature.

Active Pixel Sensors
Two types of Active Pixel Sensors (APS) devices are receiving scrutiny as alternatives to CCD vertex detectors. Hybrid devices (HAPS) [21, 22] 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), an approach based on CMOS technology, offers intrinsic spatial resolution comparable to CCDs with the advantage of avoiding charge transfer through the bulk, of better radiation hardness and of room-temperature operability. The primary R&D goals are to produce large devices with the readout speed, noise performance and thin substrates required for the LC vertex detector. The work is at present being done primarily by a European collaboration (IReS, LEPSI, RAL, U. of Liverpool, U. of Glasgow, U. of Geneva, and NIKHEF) [23, 24].

Another new technology [25] involves the DEPFET (depleted FET) concept [26], which is being pioneered as a pixel detector by a collaboration of Bonn University and MPI Munich. 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 commercially 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, and a silicon tracker with a few precise measurements per track. Technical tradeoffs are being investigated within each of these approaches. There are also 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) [27] is pursued by the North American community to address these global issues. 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, 28] is well underway at KEK, TUAT, and Kinki University, 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, and
- 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 [29] of European (Aachen, DESY/Hamburg, Karlsruhe, Kraków, MPI-Munich, NIKHEF, Novosibirsk, Orsay/Saclay, Rostock) and North American Institutes (Carleton/Montreal/Victoria, LBNL, MIT) has begun a comprehensive R&D program to address the following topics.

- Novel readout schemes to improve two-hit and point resolution, and reduce ion feedback. Technologies considered at the moment are GEM [30] and MicroMEGAS [31], which should allow for good intrinsic suppression of ion feedback. A method derived from silicon technology is also being studied. The wire-chamber alternative with high granularity [5] is being considered as a backup to and benchmark for the new technologies.
- Electronics integration to cope with $\mathcal{O}(3 \cdot 10^6)$ or more readout pads and high-speed sampling ($\sim$20 MHz or more) to exploit intrinsic longitudinal granularity, or ($\sim$100 MHz or more) to exploit induced signals on neighboring pads.
- Spatial resolution smaller than 100μm ($\sim$ 2$\times$ better than at LEP).
- Readout channel reduction via optimized pad shaping/ganging with attention to 2-track and dE/dx resolution.
- Optimized gas mixture for resolution, drift speed, sensitivity to backgrounds, ageing and implications for the field cage.

- Mechanical design to minimize material in field cages and endcaps, while providing adequate cooling for high-density electronics.
- Alignment correction techniques for coping with space charge buildup.
- Calibration schemes.
- Detailed technical simulations of readout designs with comparison to measurement of prototype devices.

Silicon Tracker

Various 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.

Silicon drift detectors are being studied by the Wayne State group [27, 32]. Detailed simulations of a silicon drift detector design for the LC have begun and the group 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.

Silicon microstrip detectors are being studied by a collaboration of UC-Santa Cruz, SLAC, Colorado, Tokyo, MIT and LPNHE Paris [27, 33]. The collaboration has begun detailed simulations of a silicon microstrip detector design and is initiating an R&D program to address the following:

- develop long ladder using existing 'Viking' chip or other ASIC technologies,
- power cycling to avoid need for active cooling,
- optimized shaping time for signal/noise, given the low expected radiation dose,
- nearest-neighbor readout for pulse centroid-finding,
- electronics of thin (less than 300μm) detectors,
- incorporation of both minimum ionizing and $1/\beta^2$ analog regimes, and
- Lorentz angle considerations.

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 [34], 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 $|\cos\theta| \sim 0.99$. 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. While silicon-based designs are getting most of the attention, other solutions need to be thoroughly examined.

The UC-Santa Cruz/SLAC collaboration [33] working on barrel silicon microstrip R&D also plans to develop simulation infrastructure for basic studies. In Korea, Kyungpook National University, Ewha Womans University, and Korea University are developing microstrip detectors for intermediate tracking and are preparing for a beamtest [35].

Both of the European and North American TPC designs also include a barrel silicon layer just inside 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 [36], 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 [36] to insert large silicon annular planes behind the endplate 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. Together with the internal Si-microstrip layers, this ensemble of Si-trackers would constitute a Si-envelope to the TPC [37], the necessity of which is being studied. 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. The issues for these detectors have much in common with the central tracking silicon detectors described above, and collaborative R&D is underway. Given the sizes of these auxiliary tracking layers, lowering manufacturing cost 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 small angles [14, 15]. Technical R&D issues include spatial resolution, material thickness, timing for bunch tagging, and calorimeter and mask splashback.

An Indiana group [27] 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.

3.2 Calorimeter

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 four-momenta. It is now broadly assumed that this will be done 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) from both the electromagnetic and hadronic calorimeters. The algorithms depend critically on the ability of separating the different components among the energy deposits in the calorimeter which in turn implies following the charged particles into the calorimeter. This requires high granularity (both longitudinal and transverse) in order to avoid double counting of charged and neutral energies as demonstrated at LEP/SLC/HERA and to assign appropriate weights in the calorimetry for software compensation; it will be verified by studies of EFAs for different types of calorimeters. The development of optimal EFAs is a significant area for R&D on its own. 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 [38].

In addition, 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.

3.2.1 Electromagnetic Calorimeter (ECAL)

The ECAL is required to measure electromagnetic showers with good energy resolution, of order $10\%/\sqrt{E}$, 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 cm^2) combined with a very small Moliere radius. Currently, the CALICE collaboration [15, 39] and U. of Oregon/SLAC [40] are pursuing the SiW option. The areas of R&D 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 in the range of $3 \times 3\text{cm}^2$ to $5 \times 5\text{cm}^2$, but the cost is significantly lower than that of the SiW option. Efforts are going on in Asia (KEK, Kobe U., Konan U., Niigata U., Shinshu U., and Tsukuba U.) [41, 42] and in Europe (Padova, Como, Trieste, Frascati) [15, 43]. 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 may be added. Shinshu U. and Konan U. [44] are studying scintillator strip arrays as a shower max detector where photon detectors are directly attached on the strips, and silicon pad arrays are being studied [43].

The use of scintillator with different decay times for the front and back parts of the calorimeter in a shaslik-type detector is also a studied option as described in [15].

c) *Other Options for ECAL.*
Scintillating crystals provide excellent energy resolutions particularly for low energy

photons even though longitudinal segmentation is difficult to implement and the cost tends to be high. A crystal option for ECAL is being studied at Caltech [45]. Also, scintillator strip arrays are being investigated for a full electromagnetic calorimeter by Kobe U. and Tsukuba U [46].

3.2.2 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 criterion for the absorber material is the effective interaction length 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 [39] 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, Kobe U., Konan U., Shinshu U., and Tsukuba U. [47].

b) *Digital calorimeter.*
High granularity can be achieved with a so-called digital calorimeter where only the hit pattern is read out and no pulse-height information is used. Several aspects of this concept are being pursued by the CALICE collaboration [39] and institutions in North America (Northern Illinois U., ANL, and U. of Utah) [48]: Candidates for the detecting medium can be RPCs (resistive plate chambers) [39, 49], GEMs (gas electron multiplier) [50], or wire chambers, each read out with pads of approximate size $\sim$1 cm^2 or small scintillator cells ($\sim$ 10 cm^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. As possible transducer options, Visible Light Photon Counters (VLPC) [51] and Silicon Photo-Multiplier (SiPM) [52] are being investigated.

3.2.3 Other Calorimeter-related Studies

a) *Low-angle Detectors*
The calorimetry at low angles includes instrumentation of the mask, covering down to about 30 mrad, and detection of beamstrahlung and pairs at very low angles, to about 5 mrad. These detectors are respectively called "low-angle tagger" (LAT) and "luminosity calorimeter" (LCAL) in the TESLA TDR [5]. The design must deal with calorimetric coverage, veto, lowest angle, crossing angle and fierce backgrounds. R&D has started [53]. Further work [54] is also being planned by Colorado [55], DESY, UCLondon, Minsk, IHEP Serpukhov and Tel Aviv, and the R&D will cover diamond

technology, crystal calorimetry with longitudinal segmentation, tungsten/gas-sampling and tungsten/Si-sampling.

b) *Photon Detectors*

Many calorimeter schemes use photon detectors for signal readout. The requirement of high-granularity motivates the development of multi-channel photon detectors. Present calorimeter designs require these devices to operate in a high magnetic-field. Therefore R&D on the following devices are on-going, aimed at high-sensitivity with magnetic-field-immunity: APD (avalanche photodiode) [1, 39, 56], HPD (hybrid photodiode), HAPD (hybrid avalanche photodiode), EBCCD (electron bombardment CCD) [1, 56], and SiPM (silicon photodiodes) [39, 52].

3.3 Muon Detector

Although the main purpose of the LC muon detectors [57] is to identify muons by their penetration through Fe, these detectors will also see significant deposits of hadronic energy since the calorimeters vary from 5.1 to 7.5 interaction lengths λ in depth. Thus, a properly instrumented muon system could also serve as backup calorimetry. Two candidate technologies, resistive plate chambers (RPCs) [58] or scintillation counter strips [59] are being studied, either of which may be used to instrument the gaps in the magnetic field iron 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 most critical issues for the muon system are the development of low cost, reliable detectors, and the studies of muon background. The institutions involved in muon detector R&D studies are: INFN-Frascati, Kobe Univ and other Asian institutes, UC Davis, Northern Illinois University, Wayne State University and Fermilab.

- Muon System Mechanical Design.
  The engineering for the muon iron requires a detailed design that considers structural loads, construction techniques and installation of iron plates, detector planes, cables, etc. It is assumed that 4-5 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 required 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 hadron decays to muons, hadron punch-through, and from muons originating far upstream should 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 must 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.

3.4 Particle ID

Particle ID derives from the measurements of many subsystems. The LC detector will surely make use of particle ID via dE/dx [60] if it is available, 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. It adds material in front of the calorimeter which will affect the ECAL performance and degrade the hermeticity, and 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 example, 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 emerging 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 many multi-jet events with several leading heavy-flavour quarks. Such events are to be found in the SM (*e.g.* Higgs decay channels, $t\bar{t}$), or beyond SM processes (*e.g.* HA which can produce 12 jets if each of the SUSY Higgs particles decay to $t\bar{t}$). 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-π 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 [61]. So far the studies have been limited to simulation and reconstruction software development within the JAS (Java Analysis Studio) framework.

3.5 Trigger and Data Acquisition

All LC detector designs include a "software trigger" as explained in the following [62]. Due to cross sections for the various physics processes differing by several orders of magnitude, highly efficient and flexible event selection and data acquisition (DAQ) are essential. The bunched operation modes of all LC designs have the common feature of a 3-order-of-magnitude longer time between bunch trains than the bunch-to-bunch separation. This suggests using the time between trains for the hardware-trigger-free and deadtime-free readout of all data generated during a whole train. Subsequent software event selection ("software trigger") using a type of filter farm will then analyse the full data to achieve the highest possible efficiency and flexibility.

All present LC detector designs are therefore based on a software trigger with the following assumptions [5]: dead time free pipeline during a bunch train, no hardware trigger, frontend pipeline with capacity for storing data from a complete train, and event selection by software.

The frontend of the subdetectors should be equipped with hit detection/zero suppression capability and readout channel multiplexing into a common readout line. Although the DAQ system for the LC detector is more relaxed than for LHC experiments, the frontend readout systems for the high granularity detectors impose demands sometimes beyond those for LHC, both for electronic integration and power consumption. This necessitates R&D for the frontend readout which must be covered by the specific subdetector groups. For the overall event building, proof of concept and the development of event selection strategies will require event-builder prototyping as well.

For the subdetectors the large number of readout channels demand development of high electronic integration and smallest possible power dissipation to reduce cooling needs, reduce dead space for the readout electronics and readout cables at the detector, achieve manageable data rates for the high granularity systems by online zero suppression, hit detection and data processing, and allow online monitoring and calibration of all frontend readout channels.

The central DAQ system itself will use commercial products available by the time it is built, and therefore no specific R&D for central DAQ hardware is warrented at this time. However for various test systems, a DAQ prototype should be provided which is based on today's commercial products. The only part of the central DAQ system needing hardware R&D is the common interface of the frontend readout systems to the central DAQ system. This common interface has to be specified and designed in close cooperation with the different detector R&D groups in order to ensure a unique interface or at least a small set of standardized interfaces for all subdetectors.

For the central DAQ mainly conceptual work is required to optimize the general design of the event building and the software event selection. A small scale central event-builder prototype using a farm of commercial computers and state-of-the-art network infrastructure could serve as a test setup to prove the concepts and develop event-filter strategies. Full event and background simulation will be essential to have as input to the prototype studies.

First tests and basic conceptual work are possible with available infrastructure as used in the FLC Farm at DESY . This infrastructure has only 100Mbit/sec network interfaces and thus cannot be used for testing event building via high speed network infrastructure, but it could serve as a prototype for test-beam applications.

The design and layout of a common frontend interface for the central DAQ could already be used in test beams. This should be done in parallel to the frontend designs of the different subdetectors prototypes in order to be ready for test beam operation and to reduce the efforts in the different R&D groups. Although first design ideas for the frontend readout have been discussed in some subdetector groups, common effort would be beneficial: this is missing up to now.

3.6 High Field Solenoid

All detector concepts under study assume a strong magnetic field of strength greater than 3T. The large volume required for this high-field magnet is a challenge, but experience is being gained by the 4T solenoid for CMS. This experience was utilized in [5] for the TESLA detector. The silicon-detector version in the American study [8] is considering a 5T solenoid which will also have a demanding design.

3.7 Machine-Detector Interface

Machine-detector interface and IP instrumentation are also important areas to study in order to achieve the anticipated physics goals. The followings topics are under investigation [63].

- 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.

- Polarization measurement.
  Accurate measurement of polarisation to $\sim 10^{-3}$, required in particular for GigaZ running, has to be developed.

- Luminosity measurement.
  Issues related to understanding the luminosity delivered at the interaction point must be fully understood. In addition to the instantaneous and total integrated luminosity, many physics analyses also require a detailed understanding of the differential luminosity spectrum (dL/dE) resulting mainly from the large beam-beam interactions in the collision process. All foreseen measurements of particle masses, for example, are highly sensitive to the exact shape of this luminosity spectrum. Methods for optimizing the delivered luminosity will also be considered in this topic, due to the significant overlap in required instrumentation.

- Beam profile.
  A monitor of Bethe-Heitler pairs at very low angles would be useful as a real-time beam diagnostic and as an independent measurement of the luminosity. A collaboration of Hawaii, KEK, and Tohoku has carried out simulations and has begun R&D on a dedicated "pair monitor"[64], based on active pixel sensor devices at very low angles near the final beam quadrupoles.

- 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.

3.8 Detectors for the $\gamma\gamma$ Collider

The final states that a $\gamma\gamma$ experiment studies [5, 6, 65] are almost identical to those in an e^+e^- experiment, leading to similar detector requirements. The photon collider hardware imposes a few requirements on the detector. Also, the photon collisions themselves lead to some additional design constraints [66].

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-clear cones.

For TESLA a storage cavity for the laser pulse has been proposed by the Max Born Institute and DESY. 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 redesign 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. LLNL has done preliminary work on characterizing the resolved photon backgrounds on the jet energy resolution [66]. 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 and the consequences are much more severe than for e^+e^- collisions. 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 vertex detector 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.

4 Test Beams

Test beams are required to obtain much of the information in order to make technical decisions for the LC detector. Especially, new ideas and extensions to existing technologies will need to be tested with beam. For example, detector designs for high-resolution and high-speed CCDs, SiW electromagnetic calorimetry, a TPC, a silicon tracker, and other large volume tracking devices, will have 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 be 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 must to be tested. Crucial concepts such as energy-flow algorithms, 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. Facilities already exist [67] at CERN, DESY, Fermilab, KEK and SLAC, but further development is warranted.

5 Conclusion

The material presented in this paper respresents the status at the time of LCWS02, August 2002 [12]. Much effort in linear collider detector R&D is already going on world-wide at universities and research laboratories. Many groups have already formed co-operations working on developments for specific detector components in an international context, and more of such co-operations are strongly encouraged. This should also facilitate the formation of experimental collaborations once the decision for a linear collider facility has been taken.

Given the challenging detector performances envisaged, it is necessary to strengthen the R&D efforts and to ensure coverage of all areas including simulation and reconstruction codes. This has been realized by the experimental community and interest in linear collider detector R&D is growing rapidly. In fact, many recent new proposals are not yet included here, since they are still in the preparatory stage. Therefore, this paper can only represent a first step towards informing the community. A web page [10] has been created with links to linear collider detector R&D projects. It will be kept up-to-date by the international contact persons. The information provided should ease the identification of uncovered or inadequately covered areas.

The physics programme of the linear collider is compelling and will be a formidable challenge for the detector. The world-wide effort now being mounted to meet this challenge is reflected in this document.

References

[1] K. Abe et al, *Particle Physics Experiments at JLC*, KEK-Report 2001-11, hep-ph/0109166.

[2] *ACFA Joint Linear Collider Physics and Detector Working Group*
http://acfahep.kek.jp/

[3] J.A. Aguilar-Saavedra et al, TESLA Technical Design Report, Part III, *Physics at an* e^+e^- *Linear Collider*, DESY 2001-011, ECFA 2001-209, hep-ph/0106315.

[4] *2nd Joint ECFA/DESY Study on Physics and Detectors for a Linear Electron-Positron Collider*
http://www.desy.de/conferences/ecfa-desy-lc98.html

[5] TESLA Technical Design Report, DESY 2001-011, ECFA 2001-209.

[6] T. Abe et al, *Linear Collider Physics Resource Book for Snowmass 2001*, BNL-52627, CLNS 01/1729, FERMILAB-Pub-01/058-E, LBNL-47813, SLAC-R-570, UCRL-ID-143810-DR, LC-REV-2001-074-US, hep-ex/0106055-58

[7] *A Study of the Physics and Detectors for Future Linear* e^+e^- *Colliders: American Activities*
http://blueox.uoregon.edu/~jimbrau/LC/ALCPG/

[8] *Worldwide Study of the Physics and Detectors for Future* e^+e^- *Colliders*
http://lcwws.physics.yale.edu/lc/

[9] http://lcwws.physics.yale.edu/lc/committee.html

[10] http://blueox.uoregon.edu/~lc/randd.html

[11] http://committees.web.cern.ch/Committees/DRDC/Welcome.html/

[12] LCWS1991 at Saariselkä, Finland: *Physics and Experiments with Linear Colliders*, eds. R. Orava, P. Eerola and M. Nordberg, World Scientific, Singapore, 1992.
LCWS1993 at Waikoloa, Hawaii: *Workshop on Physics and Experiments with Linear* e^+e^- *Colliders*, eds. F.A. Harris, S.L. Olsen, S. Pakvasa and X. Tata, World Scientific, Singapore, 1993.
LCWS1995 at Morioka, Japan: *Workshop on Physics and Experiments with Linear Colliders*, eds. A. Miyamoto, Y. Fugii, T. Matsui and S. Iwata, World Scientific, 1996.
LCWS1999 at Sitges, Spain: *Proceedings of the Worldwide Study on Physics and Experiments with Future Linear* e^+e^- *Colliders*, eds. E. Fernández and A. Pacheco,

Universitat Autònoma de Barcelonaa, Servei de Publicacions, 1999.
LCWS2000 at Batavia, Illinois: *Physics and Experiments with Future Linear* e^+e^- *Colliders*, eds. A. Para and H.E. Fisk, AIP Conference Proceedings, Vol.578, 2001.
LCWS2002 at Jeju, Korea: *International Workshop on Linear Colliders*, August 26–30, 2002, proceedings to be published.

[13] G. Loew et al, Report of the International Linear Collider Technical Review Committee, http://www.slac.stanford.edu/xorg/ilc-trc/ilc-trchome.html

[14] M.N. Frary and D.J. Miller, in: e^+e^-*-Collisions at 500 GeV: The Physics Potential, Parts A and B*, Workshops at Munich, Annecy, Hamburg, 1991, ed. P.M. Zerwas, DESY 92-123A&B (1992), p.379, and
K. Mönig, *Forward tracking and measurement of the luminosity spectrum at TESLA*, Proceedings of LCWS2000 (see list in Ref.[12]), pp. 829-832.

[15] TESLA Technical Design Report, Part IV, *A Detector for Tesla*, DESY 2001-011, ECFA 2001-209, hep-ph/0106315.

[16] 1995 ILC-TRC Technical Review Committee Report (Loew Panel) on the different LC machine designs, http://www.slac.stanford.edu/xorg/ilc-trc/ukc-trcgine.html. Updated report due in 2002; it will also include background and IR issues.

[17] K. Abe et al, Nuc. Inst. Meth., **A400**, 287 (1997).

[18] LC-DET-2001-023, UK PPESP proposal and DESY PRC R&D 01/01 of 19 March 2001,
UK PPRP proposal of 30 April 2002

[19] http://hep.ph.liv.ac.uk/ green/lcfi/home.html

[20] FY01 proposal for vertex detector studies submitted to SLAC Prescott Committee;
J. Brau et al, proposal submitted to U.S. DOE Advanced Detector Research Program, October 2001;
H. Neal, presentation at the Chicago Linear Collider Workshop, January 7-9, 2002, http://lcworkshop.uchicago.edu/.

[21] IEEE NSS contribution, LC-DET-2001-042

[22] http://home.cern.ch/~caccia

[23] LC-DET-2001-017, DESY PRC R&D 01/04

[24] http://ireswww.in2p3.fr/ires/recherche/capteurs/index.html

[25] P. Fischer et al, TESLA Note LC-DET-2002-04.

[26] J. Kemmer and G. Lutz, Nucl. Inst. and Methods A253 (1987) 365.

[27] FY01 JointR&D Proposal for Linear Collider Tracking, submitted to SLAC Prescott Committee, accessible via web page of North American Working Group on Linear Collider Tracking at http://www-mhp.physics.lsa.umich.edu/~keithr/trkmain.html.

[28] K. Fujii, in "Physics and Experiments with Future Linear e^+e^- Colliders", eds. A. Para, H.E. Fisk, AIP Press, 2001, and extensive references therein.

[29] The LC TPC group, "LC TPC R&D, A Proposal to the DESY PRC", DESY-PRC R&D 01/03 (Oct.2001).
http://www.physik,rwth-aachen.de/group/IIIphys/TESLA/TESLA_en.html
http://www.lbl.gov/~ronan/docs/lctpc
http://www.physics.carleton.ca/~karlen/gem
http://www.desy.de/flc/LC/tpc.html
http://www.lal.in2p2.fr/recherche/flc
http://www-dapnia.cea.fr/Spp/Experiences/FELICE/tpc_micromegas.shtml
http://alephwww.mppmu.mpg.de/~settles/tpc/welcome3.html

[30] F. Sauli, Nucl. Inst. Meth. **A386**, 531 (1997).

[31] Y. Giomataris et al, Nucl. Inst. Meth. **A376**, 29 (1996).

[32] V. Rykov, presentation at the Chicago Linear Collider Workshop, January 7-9, 2002, http://lcworkshop.uchicago.edu/.

[33] D. Dorfan et al., proposal submitted to U.S. DOE Advanced Detector Research Program, October 2001;
B. Schumm, presentation at the Chicago Linear Collider Workshop, January 7-9, 2002, http://lcworkshop.uchicago.edu/.

[34] A.F. Fox-Murphy et al, Nuc. Inst. and Meth. **A383**, 229 (1996).

[35] H. Park, private communication.

[36] J.E. Augustin, M. Bergren and A. Savoy-Navarro, "Study of Silicon External Tracker SET", LC-DET-2001-075.

[37] J.E. Augustin et al., "A Si envelope for the TPC", submitted as LC-DET Note, 12 June 2002, and in http://www-lpnhep.in2p3.fr/lineaire/lcnotes/

[38] T. Kamon (Texas A&M), a proposal to the Prescott committee (funded).

[39] DESY PRC-R&D 01/02 and DESY PRC-R&D 01/02 Memo-01,
http://polywww.in2p3.fr/tesla/calice.html.

[40] R. Frey et. al. (U. of Oregon) and M. Breidenbach (SLAC), a proposal to the Prescott committee (funded).

[41] KEK, Niigata Univ., and Tsukuba Univ.; A.Sanchez, "Bench Test of Small Plastic Scintillator Tiles for JLC EM Calorimeter", Accelerator and Particle Physics Institute, Appi, Feb. 2002; A.Sanchez, JPS meeting at Kusatsu, March 2002.

[42] Particle Physics Experiments at JLC, Part III, *Detectors*, KEK Report 2001-11.

[43] DESY PRC-R&D 00/02

[44] F. Kajino et. al., Nucl. Inst. Meth. **A383** (1996) 260; K. Kawagoe in LCWS2000 Proceedings, ed. A. Para (AIP Conference Proceedings, 2001).

[45] http://www.hep.caltech.edu/~zhu/

[46] Tsukuba Univ.; K.Sekiguchi, JPS meeting at Kusatsu, March 2002

[47] T.Suzuki et. al., Nucl. Inst. Meth. **A432** (1999) 48.

[48] http://nicadd.niu.edu/dhcal/

[49] J. Repond, S. Magill et. al. (Argonne National Laboratory), http://www.hep.anl.gov/repond/Opportunities.ppt

[50] A. White et. al. (UT Arlington), http://nicadd.niu.edu/dhcal/talks/DHCAL_050902.ppt

[51] G. Blazey et. al. (Northern Illinois), http://nicadd.niu.edu/preprints/DHCAL_Proposal_2001.doc

[52] http://www.slac.stanford.edu/pubs/icfa/fall01/paper3/paper3a.html

[53] T. Behnke et. al., LC-DET-2002-01, http://www.desy.de/lcnotes/LCnotes_welcome.html.

[54] A. Stahl, private communication. Proposal to be submitted to the next DESY PRC in Oct. 2002

[55] U. Nauenberg et. al. (U. of Colorado), a proposal to the Prescott committee (funded).

[56] Y. Fujii et. al., Nucl. Instr. Meth. **A366** (1995) 71: N. Kanaya et.al., Nucl. Instr. Meth. **A421** (1999) 512.

==========================

[57] D. Koltick, "Muon and Other Particle Identification at a Linear Collider", LCWS1999 at Sitges, Spain: *Proceedings of the Worldwide Study on Physics and Experiments with Future Linear* e^+e^- *Colliders*, eds. E. Fernández and A. Pacheco, (Universitat Autònoma de Barcelonaa, Servei de Publicacions, 1999),p. 701
D. Koltick and N. Morgan, "Low Cost Muon Detector", ibid., p. 977
K. Kawagoe, "The Muon Detector for the JLC Experiment", ibid., p. 984

G. Bruni and M. Piccolo, "A Muon Detector for TESLA", ibid., p. 992
M. Piccolo, "Muon and Special Detectors Summary", *"Physics and Experiments with Future Linear e^+e^- Colliders"*, LCWS2000, Batavia, Illinois, eds. A.Para, H.E. Fisk, AIP Press, 2001. p. 855

[58] M. Piccolo, "A Muon Detector for TESLA", *"Physics and Experiments with Future Linear e^+e^- Colliders"*, LCWS2000, Batavia, Illinois, eds. A.Para, H.E. Fisk, AIP Press, 2001. p. 870

[59] A. Para, "Solid Scintillator-based Muon Detector for Linear Collider Experiments", *"Physics and Experiments with Future Linear e^+e^- Colliders"*, LCWS2000, Batavia, Illinois, eds. A.Para, H.E. Fisk, AIP Press, 2001. p. 865

[60] H. Yamamoto, "dE/dx Particle Identification for Collider Detectors," 1999 ACFA Workshop, Seoul, Korea, hep-ex/9912024.

[61] R. Wilson, private communication.

[62] G. Eckerlin, private communication.

[63] http://www.slac.stanford.edu/~torrence/ipbi

[64] G. Alimonti, in "Physics and Experiments with Future Linear e^+e^- Colliders", eds. A. Para, H.E. Fisk, AIP Press, 2001.

[65] KEK-Report 97-17

[66] J. Gronberg, private communication.

[67] G. Fisk, "Test Beams: Availability and Plans," LCWS2002 at Jeju, Korea, August, 2002, http://www-lc.fnal.gov/lc_testbeams/