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Calorimetry and Muons

A.P.White
University of Texas at Arlington, Arlington, TX76019

The status of studies for the calorimeter and muon subsystems for future ILC detector(s) is reviewed.

1. INTRODUCTION AND OVERVIEW

This paper describes the status of studies for the calorimeter and muon systems for future ILC detectors. The calorimeter is arguably the most critical subsystem for an ILC detector, given its role in high precision jet energy and jet-jet invariant mass measurements. The Energy Flow Algorithm (EFA) approach is the leading candidate to deliver the required precision, and its implementation is intimately connected with the detailed design of the calorimeter system. Examples of challenging physics processes driving the designs of the subsystems will be given, and their translation into specific design requirements will be described. The traditional approach to calorimetry will be contrasted with the EFA approach, emphasizing the integrated or "whole detector" aspects of the latter. The status of R&D for the electromagnetic and hadronic calorimeters, and the muon system/tail-catcher will be reviewed, with many examples.

Finally, the timeline for development, test beams, and eventual detector construction will be discussed.

2. THE CALORIMETER SYSTEM

2.1. Examples of physics processes driving calorimeter design

Many physics processes have W-, and Z-bosons, and Higgs particles in their final states, for instance:

$$e^+e^- \rightarrow Zh, WW, ZZ$$

$$e^+e^- - \; t\bar{t}h - \; WWbbbb$$

For reasons of rate, these objects must be reconstructed in all jet modes, demanding efficient jet separation and reconstruction, unprecedented jet energy resolution and jet-jet mass resolution.

In addition, a number of supersymmetric processes require the provision of very good forward calorimetry, and the ability to find and reconstruct photons from secondary vertices.

2.2. Calorimeter and Overall Detector Design

Two general approaches have been taken to overall design.

(1) Large calorimeter inner radius. In this approach the calorimeter inner radius is made sufficiently large to achieve good separation of electrons, photons, charged hadrons and jets. This fits well with a large volume tracking system with many measurements per charged track. Good momentum resolution is obtained with a moderate magnetic field (B) and the large tracker radius (R), since the resolution depends on the combination

BR^2. The negative aspect to this approach is that the calorimeter and muon systems become large and potentially very expensive. However, a larger radius for the calorimeter system may allow a traditional approach, as opposed to new, digital/EFA design described later in this paper. The Large Detector Concept (LDC) and the Global Large Detector (GLD) (Figure 1) fall in this category of detector design.

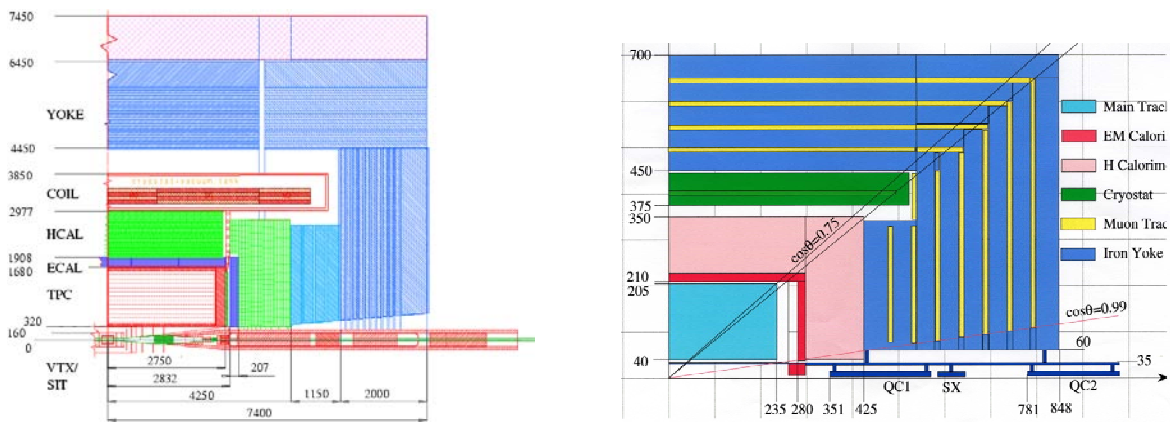

Figure 1: Large Detector (left) and GLD Detector (right) Concepts

(2) Compact detector – reduced inner calorimeter radius. This approach, followed in the SiD Detector design concept (Figure 2), assumes the use of Silicon-Tungsten technology for the electromagnetic calorimeter. This allows small cells which provide excellent energy resolution and separation of charged hadrons from electromagnetic showers. The cost of the electromagnetic calorimeter is constrained by the limited radius, which, in turn, implies a compact tracking system. This tracking system is implemented in silicon technology with point measurement at the level of 10 micron. Finally, to restore the value of the BR^2 parameter, and hence the quality of the momentum resolution, the magnetic field is anticipated to be set at 5 Tesla.

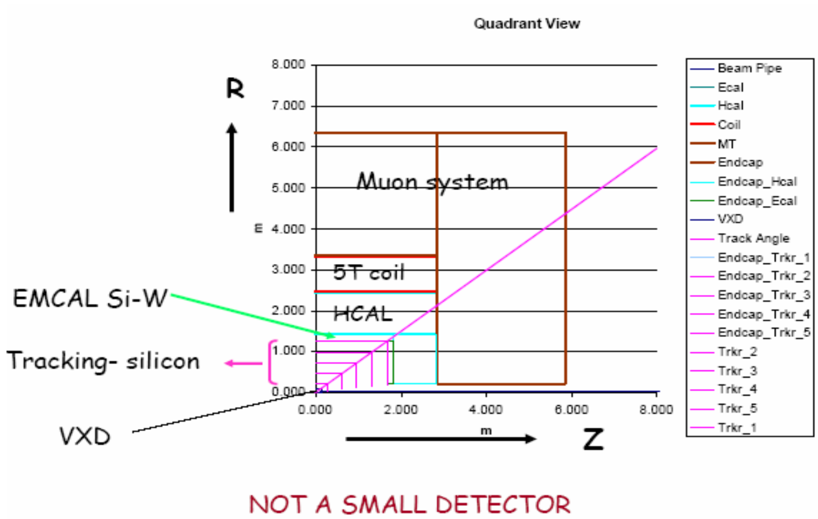

Figure 2: SiD Detector Concept

2.3. ILC Calorimetry requirements: Traditional and Energy Flow Approaches.

In order to achieve the required separation of W-, Z-bosons, and Higgs particles in their hadronic decay modes studies [1] have shown that jet energy/jet-jet mass resolution in the region of 30%/ E is needed. By contrast, traditional existing calorimeter systems fall short of this requirement. For instance the ZEUS Uranium/Scintillator calorimeter has a jet energy resolution of 50%/ E, while the DZero Uranium/Liquid calorimeter has a jet energy resolution of 80%/ E. Clearly a significant improvement is needed for an ILC detector.

A possible approach to enhancing the performance of traditional calorimetry has been taken by the DREAM (Dual REAdout Module) project [2]. A direct measurement of the electromagnetic components of showers from jets is made using quartz fibers in combination with scintillating fibers for energy measurement. This approach can potentially lead to improved jet energy resolution by overcoming both the unequal response to electromagnetic and non-electromagnetic shower components, and the large event-to-event fluctuations in the electromagnetic energy fraction. Promising results for individual hadron energy resolution are shown in Figure 3. The main issue is how to configure this technology, with its very large number of fibers, for a practical calorimeter system.

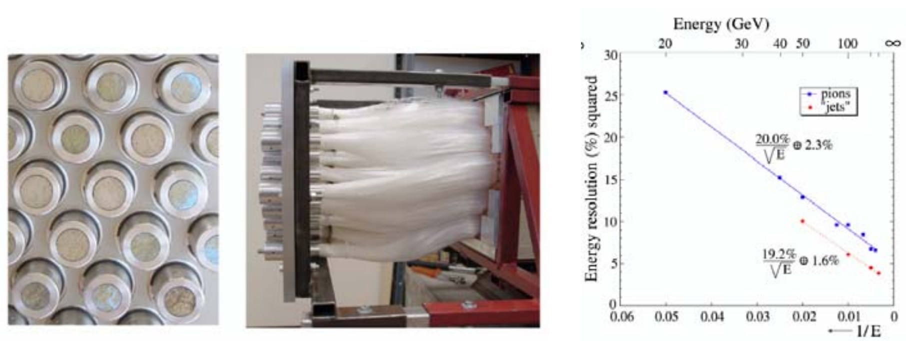

Figure 3: DREAM calorimeter project; prototype (left), results (right).

Recently, considerable effort has been put into an alternative approach, known generally as Energy or Particle Flow Algorithms (EFA). The EFA has already been used effectively in other experiments [3], but its ability to deliver the jet energy resolution required for ILC calorimetry still remains to be proved. This will require a substantial amount of algorithm development, already underway, and test beam studies of new detector implementations to verify the technologies and the simulation code.

The basis for the EFA is the recognition that measurement of the transverse momenta of charged particles, usually the dominant component of jets, using the tracking system, is superior to traditional energy measurement in the calorimeter. Photons are measured as usual in the electromagnetic calorimeter. Once the energy deposits associated with the charged tracks have been identified, only the relatively small neutral hadron component remains to be directly measured in the hadron calorimeter. This de-emphasizes the importance of the intrinsic energy resolution of the hadron calorimeter, but highlights the need for very efficient “pattern recognition” in the calorimeter. The so-called “confusion term” arising from mis-association of tracks and energy deposits must be aggressively minimized if superior jet energy resolution is to be achieved. Finally, the energy leakage from the rear of the hadron calorimeter into the muon system is measured through the use of a tail-catcher integrated into the front of the muon system itself.

The complexity of the task of implementing the EFA approach should not be underestimated. Figure 4 shows an example of the pattern of energy depositions from a $e^+e^- - WW$ event at 800 GeV center of mass energy (Ref.xxx).

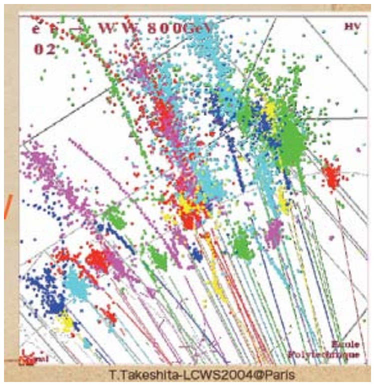

Figure 4: Complex energy deposition pattern, from [17].

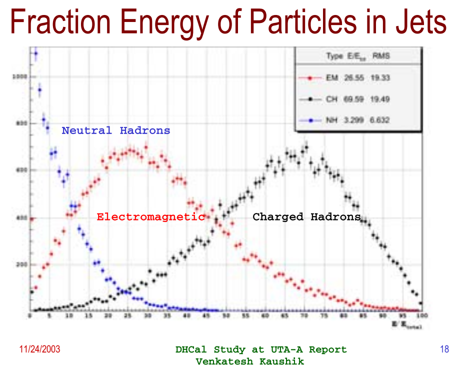

Figure 5: Jet fractional energy composition

Added to this typical complexity are the event-to-event fluctuations. Figure 5 shows the fractional composition of a jet from $e^+e^- - tt$ events. It has become popular to quote the averages of these distributions in recent talks. However, the distributions are clearly wide and the EFA's will have to cope with substantial variations in jet composition. For instance, an event could consist of 25% neutral hadrons, 40% electromagnetic component, and 35% charged hadrons. It is a challenging task to find all neutral clusters in such an event and not mis-associate them with charged track(s).

2.4. Integrated Detector Design

The use of the EFA approach requires a much more integrated approach to detector design than has been traditional. The tracker must not only provide excellent momentum resolution, certainly good enough for replacing cluster energies in the calorimeter with track momenta, but must also efficiently find all charged tracks. Any missed tracks will result in the corresponding energy clusters being measured with lower energy resolution and a potentially larger confusion term. The tracker must also provide excellent two-track resolution for correct track/cluster association. The need for an integrated design view is particularly evident here in terms of relating the tracker outer radius, and magnetic field size, to the issue of separating electromagnetic showers (and hence the Moliere radius) in the electromagnetic calorimeter.

The calorimeters should provide excellent MIP identification for muon tracking between the tracker and the muon system itself. High granularity calorimeters should naturally provide this, but the required granularity must be carefully studied. We must also be able to find and track low energy muons completely contained within the calorimeter, and be able to use the fine granularity to identify secondary, off-angle, decays of, for instance, long-lived SUSY particles. Finally, there are the usual considerations of hermeticity and dead material. For instance, the services for the vertex detector and tracker should not cause large penetrations, spaces, and/or dead material within the calorimeter system – thus having implications for the design of the inner subsystems.

2.5. Calorimeter System Design

In general, two design variants have been studied in detail:

(1) An analog electromagnetic calorimeter in combination with an analog hadron calorimeter.

(2) An analog electromagnetic calorimeter in combination with a digital hadron calorimeter.

For (1) there is the question of cost for the readout with the large number of channels needed to achieve the required granularity, while for (2) the intrinsic resolution (for the measurement of the residual neutral energy after charged cluster removal) of a purely digital hadron calorimeter remains to be fully understood.

2.6. Calorimeter Technologies – Electromagnetic Calorimeter

In this section, first the general characteristics and requirements of the electromagnetic calorimeter are discussed. Then a survey is given of the various R&D projects underway to develop specific implementations of electromagnetic calorimetry.

The physics requirements deriving from studies of processes such as those described in 2.1 emphasize segmentation/granularity (both transverse and longitudinal) over intrinsic electromagnetic energy resolution. Thus it is thought that a resolution in the range 10-15%/ E should be sufficient for the latter. Localization of the electromagnetic showers and electromagnetic particle/hadron separation argue for a dense (small X_0) electromagnetic calorimeter with fine segmentation, a Moliere radius of O(1cm), and a transverse segmentation of the same size as the Moliere radius. Charged particle/photon separation may benefit from a finer transverse segmentation in the first few layers of the calorimeter. Tracking charged particles through the calorimeter, for use in the EFA's requires fine longitudinal segmentation and high MIP efficiency, while the fine segmentation overall should allow excellent photon direction determination – for instance from secondary decays of particle under the gauge-mediated supersymmetry breaking. Finally, of course, for a silicon-based device, the cost must be kept under control.

a) Silicon-Tungsten technology

Several groups are studying the use of silicon as an active medium in combination with tungsten absorber. The SLAC-Oregon group design [4] is shown in Figure 6 and uses an on-board ASIC to readout a large number of cells. The goal is to achieve a total active gap thickness less than 1mm. The basic cell transverse dimension is 1cm. First sensors are currently under test and dimensionally acceptable tungsten plates have also been made.

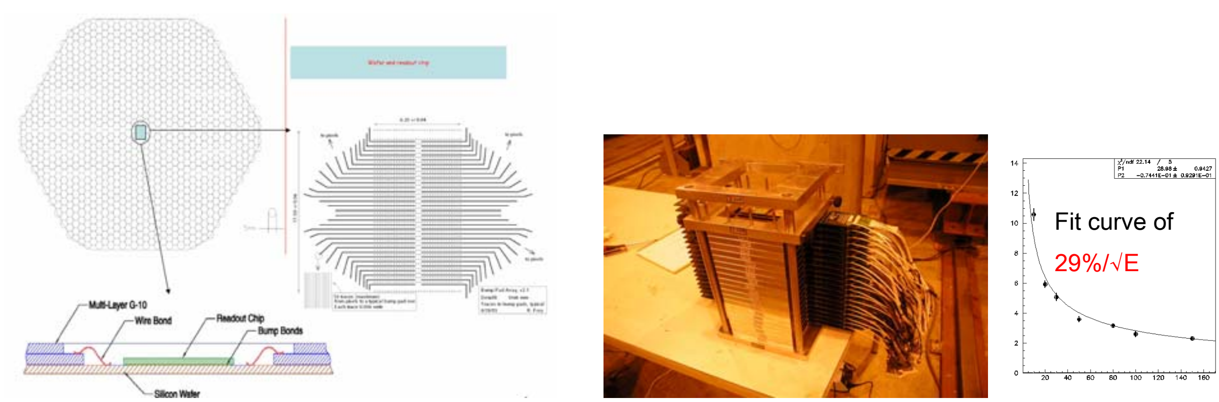

Figure 6: SLAC-Oregon(left) and Korean (right) SiW Electromagnetic CalorimeterDesigns

The CALICE collaboration [5] is also constructing a SiW prototype with Si wafers being processed by Moscow State and Prague. A partial (30%) depth module has already been exposed to an electron beam at DESY and results presented at this meeting, (see [6] and Figure 7). A full-depth prototype is under construction and will have the characteristics shown in Figure 7. It is noted that a recent new design has resulted in a 40% reduction of the active gap thickness from an initial value of 1.4mm. In parallel, there has been continuous evolution of the front-end readout chip design.

Finally, a SiW prototype has been built and tested by a group from Korea [7]. A view of their module is shown in Figure 6. together with a resolution curve from a test beam run at CERN in 2004. The observed 29%/ E is not in good agreement with the their quoted GEANT4 result of 18%/ E.

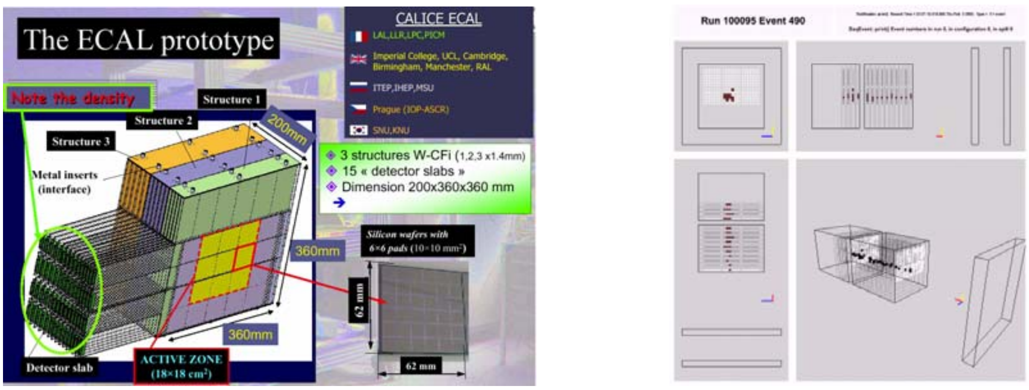

Figure 7: CALICE Collaboration electromagnetic calorimeter prototype(left), and an event from a partial-depth exposure to an electron test beam at DESY (right).

b) Scintillator-based technology

A Japan-Korea-Russia collaboration [8] is working on a prototype with fine granularity achieved by the use of a combination of scintillator strips and small scintillator tiles readout using SiPM's. Figure 8 shows a previous prototype readout using MAPMT's, and the new SiPM-based design. The aim is for a test beam exposure at CERN in 2006.

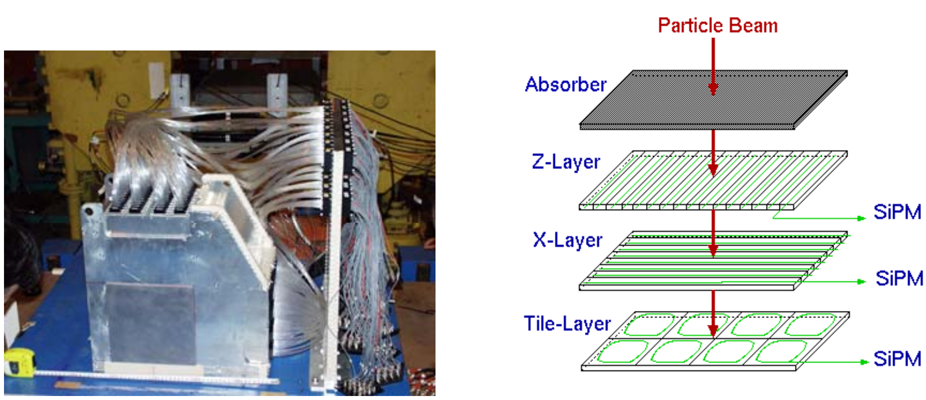

Figure 8: Japan-Korea-Russia Lead-Scintillator electromagnetic calorimeter prototypes.

An alternative geometry using scintillator tile/fiber technology is being studied by the U. Colorado group [9]. This arrangement is shown in Figure 9 and features a half cell offset to achieve an effective tile size reduction. Simulations indicate an expected resolution ~11-12%/ E. The group is also pursuing readout electronics development with industry.

Finally, the LC-CAL (INFN) group is developing a hybrid prototype based on Lead-Scintillator planes plus three silicon pad layers at 2, 6, and 12 X_0. A view of the module is shown in Figure 9. An energy resolution of 11-11.5%/ E has been measured, and a position resolution of ~2mm (@30 GeV.

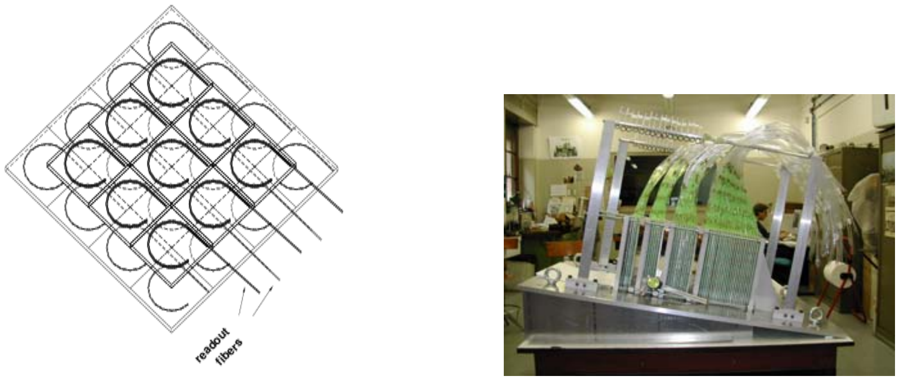

Figure 9: U. Colorado halfcell offset tile layout (left); LC-CAL(INFN) hybrid module (right).

2.7. Calorimeter Technologies – Hadron Calorimeter

In this section first the general characteristics and requirements of the hadron calorimeter are discussed. Then a survey is given of the various R&D projects underway to develop specific implementations of hadron calorimetry. The potential use of EFA's emphasizes segmentation, both longitudinal and transverse, over intrinsic energy resolution. However, the intrinsic energy resolution for single neutral hadrons must not degrade the jet energy resolution. Assuming an EFA approach, sufficient segmentation is required to allow efficient charged particle tracking, and for the digital approach, sufficiently fine segmentation is required to give a linear energy vs. hits relationship. In addition, the whole system should have very efficient MIP detection. Finally, radially, the hadron calorimeter should have a depth of about four interactions lengths to contain hadronic showers.

There have been two general approaches to implementing hadron calorimetry: scintillator-based, and gas-based. The gas-based approach has two main techniques for the active layer: Gas-Electron Multipliers (GEM) and Resistive Plate Chambers (RPC), with both taking the digital approach of only recoding a hit, or no hit, in each cell. Since the digital approach is a new idea, it will require extensive testing with beam to verify performance and to check the accuracy of the simulation software – as a precursor to final design work. All three designs discussed here are being developed within the CALICE collaboration [10], and all three efforts have as a goal the creation of 40-layer 1m^3 modules for test beam exposure over the next 1-3 years.

a) Scintillator-based technology.

The main obstacle to implementing a scintillator/fiber solution, how to deal with an external fiber mass, has been neatly dealt with by the introduction of Silicon Photomultipliers (SiPM), that have been shown to have the required sensitivity (visible single and multiple photoelectron peaks). Each SiPM is very small, O(1mm diameter), and is inserted into a small recess in the scintillator tile. Figure 10. shows a view of a single layer cassette under construction at DESY. Also shown is a schematic of a test beam module support assembly, to be provided by DESY, that will carry each of the three 1m^3 modules. Each layer has 3x3 cm^2 tiles at the center, with larger tiles toward the outside edges.

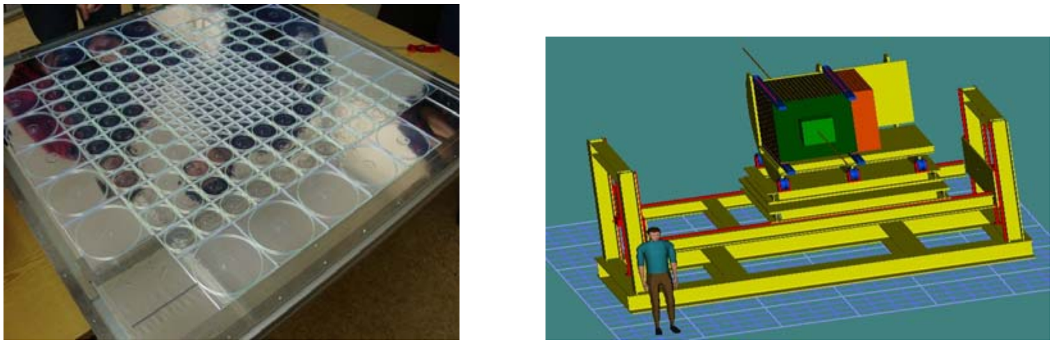

Figure 10: Scintillator/fiber cassette (left), and 1m^3 module support structure design schematic.

b) Gas-based technology.

A group from U. Texas at Arlington, U. Washington, Changwon U.(Korea) and Tsinghua U. (China) is developing technology based on a double-GEM structure [11]. A schematic of this approach is shown in Figure 11, together with a large-scale mechanical prototype of a 1/3 calorimeter layer. Many results have been presented [12] showing high track efficiency, low multiplicity, and reliability of operation over extended periods. The next stage will be a stack of five 30x30 cm^2 chambers, using new foils from 3M, with a total of 500-channels as a precursor to the full 1m^3 stack.

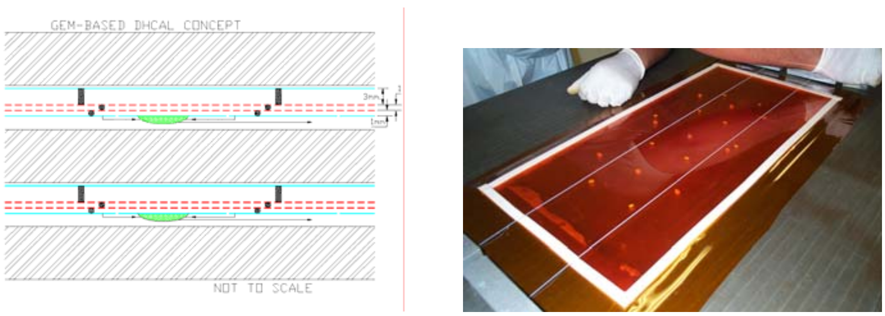

Figure 11: Gas Electron Multiplier based digital calorimetry. Schematic (left), large layer (right).

A group from Argonne National Laboratory, U. Chicago, and Iowa State, is developing technology based on RPC’s [13]. A schematic of this approach is shown in Figure 11, plus, as an example, one result from a wide range of tests. The RPC planes have been developed to the point where they are ready for full-scale construction of a 1m^3 test beam stack.

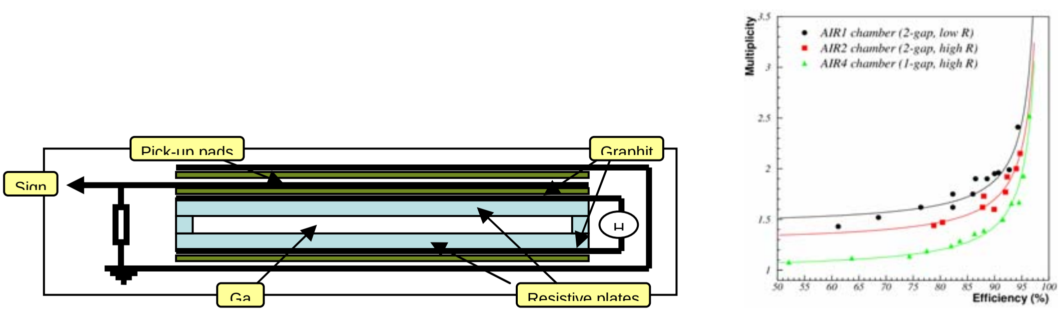

Figure 12: RPC-based digital calorimetry. Schematic (left), and multiplicity measurements (right).

There is also a large scale electronic readout project underway for both the RPC and GEM modules working with the PPD Electronics group at Fermilab. A first run ASIC will be available for testing in Summer 2005.

3. MUON SYSTEM AND TAIL-CATCHER

Muon identification and measurement are essential for the ILC Physics program. Also, it is important to identify and measure any leakage of energy from the hadron calorimeter. The roles of the muon system/tail-catcher are therefore to identify high transverse momentum muons exiting the calorimeter/coil, contribute (with the tracking system) to the muon momentum measurement, possibly identify long-lived particles penetrating deep into the detector, and measure the tail energies of hadron showers. Muon system technologies under investigation include scintillator and RPC's. A U.S. collaboration [14] is building pre-prototypes using extruded scintillator strips with wavelength-shifting fibers, read out using multi-anode photomultipliers. The European CAPIRE collaboration [15] is using a silk-screen printing approach to producing large area RPC's. Finally, a CALICE-Northern Illinois U. group [16] is using the extruded scintillator approach with SiPM's for a tail-catcher design. A view of each of these techniques is given in Figure 13.

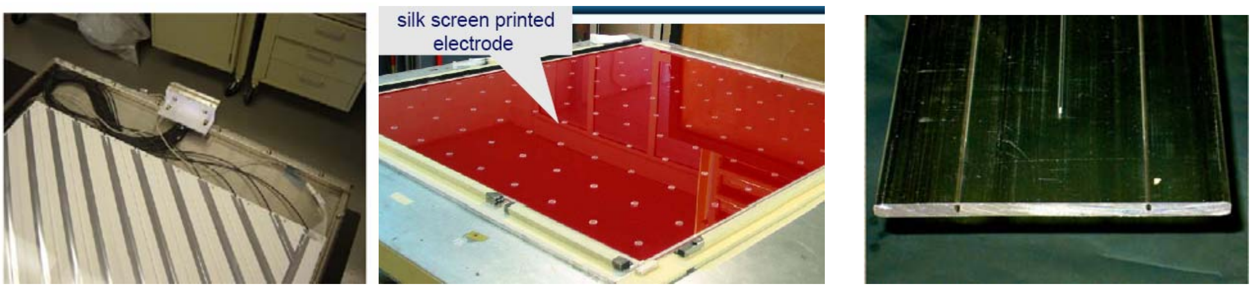

Figure 12: Muon/tail-catcher designs. Scintillator-WLS fiber (left), RPC (center), extruded scintillator (right).

4. TIMESCALES FOR CALORIMETER AND MUON SYSTEM DEVELOPMENT

If the overall timeline for the ILC from the GDE is followed, then we have a period of 3-5 years to build, test, and understand calorimeter and muon system technologies prior to actual detector final design and construction. By "understand" we mean that the cycle of testing, data analysis, re-testing etc. should have converged to the point at which we can reliably design calorimeter and muon systems from a secure knowledge base. For the calorimeter, the is means having trusted Monte Carlo simulations of technology(s) at unprecedented small distance scales, O(1cm), well-understood energy cutoffs,, and demonstrated, efficient, complete energy flow algorithms. Since the first modules are only now being built, 3-5 years is not an over estimate to accomplish these tasks.

5. CONCLUSIONS

A review has been presented of the status of research and development for calorimeter and muon systems for future ILC detector(s). It is clear that at present there are a number of parallel and overlapping efforts. This is inevitable, and even desirable, during the initial ILC detector R&D phase. However, funding is generally limited and we must make optimal use of those resources we have. It is noted that the World Wide Study for the ILC has formed an R&D Panel. Each detector concept group, and individual research effort, will provide input to this panel with the goal of specifying the required levels of support, and the efficient use of R&D resources during the next phase of development.

References

[1] H.Videau talk at LCWS04, "Energy Flow and Particle Flow", Paris, France, April 2004.

[2] Nuclear Instruments and Methods in Physics Research Section A: Volume 537, Issue 3, 1 February 2005, pp 537-561 .

[3] See for example the D0 Experiment, D0 Note 3927 "An energy flow algorithm for D0", Laurent Duflot and Melissa Ridel, and the ALEPH Experiment, "Performance of the ALEPH detector at LEP" NIM A 360 (1995) 481.

[4] David Strom, "First results with the prototype detectors of the Si/W ECAL", talk at LCWS05, http://www.pd.infn.it/~checchia/lcws05/strom-cal.pdf.

[5] http://polywww.in2p3.fr/flc/calice.html

[6] CALICE Si/W ECAL prototype, first testbeam results, G.Mavromanolakis, talk at LCWS05, http://polywww.in2p3.fr/~videau/lcws05/Mavromanolakis.pdf.

[7] Talk at this conference: Shinwoo Nam, (EWHA) "CERN Beam Test of Silicon-Tungsten Calorimeter Test Module".

[8] Talk at this conference: Hitoshi Miyata (Niigata) "R&D of Calorimeter Using Striplet/Block Scintillators with SiPM".

[9] "Report on Tile R&D", U. Nauenberg at Victoria Linear Collider Workshop, July 2004.

[10] http://polywww.in2p3.fr/flc/calice_HCAL.html.

[11] Talk by the author, "Report on UTA HCal R&D", at the Victoria Linear Collider Workshop, July 2004.

[12] Talk by the author at this conference: Development of GEMS.

[13] Talk at this conference: Lei Xia, "Developments on RPC's".

[14] Talk at this conference: R. Abrams, "Tests of a Preprototype ILC Muon Detector Module".

[15] Talk at Victoria Linear Collider Workshop, July 2004, M. Piccolo, "μ detector R&D in Europe".

[16] Talk at this conference: Dhiman Chakraborty, "CALICE TCMT Status/Plans".