SiD Detector – Hadron Calorimeter Five-Year R&D Plan

Draft 11/9/06 – Andy White
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Updated with J.Jaros comments 1/22/07 Andy White

Introduction

This plan was developed prior to the recently proposed accelerated schedule for defining just two detectors for the ILC. However, assuming that SiD proceeds as one these two detectors, the necessary steps for defining the HCal prior to writing a CDR remain the same.

The issue we are concerned with here is the development schedule for the HCal in the context of the known schedules for the CDRs and EDRs, and a sensible schedule for selection of a final technology. We therefore discuss a five year plan covering approximately until mid-2008 to complete a CDR, and a further three years to complete a EDR. The plan encompasses HCAL technology selection, PFA development, and overall engineering requirements.

Requirements

The hadron calorimeter is a critical component of the SiD detector as it provides essential information for the identification and reconstruction of jets and other physics objects via a Particle Flow Algorithm. The basic requirements for this device are:

- It must efficiently allow tracking of charged particles through its volume.
- It must have sufficient depth such that any energy loss in the coil, and/or energy measured with degraded resolution (relative to the HCal) in the outer detectors (such as a TCMT) does not significantly impact jet energy resolutions at all jet energies.
- It must have a sufficiently small cell size to allow true separation and association of closely spaced energy clusters with the correct tracks – at a level that does not significantly degrade the jet energy resolution.

- It must have a sufficient sampling so as not to significantly degrade the jet energy resolution via the sampling term.
- Its outer radius must limit the cost of the solenoid and muon system to reasonable levels – requiring the radial size of each active layer to be as small as possible.
- It must have sufficient rate capability so as not to lose information, particularly in the forward directions – using a change of technology, if necessary.

Technologies for the Hadron Calorimeter

A number of possible implementations have been proposed for the HCal active layers; gaseous technology in the form of RPC's, GEM's, and micromegas; and plastic technology in the form of scintillator tiles. These are not described in detail here having been the subject of many presentations. The recently proposed micromegas implementation would be very similar to the GEM version, with the GEM foils replaced by the micromegas mesh.

Technology selection for the HCal Active Layers

There are many factors that will play into the final selection of a technology for the SiD HCal. *The main issue will be the quality of overall ECal and HCal physics performance versus the cost of the HCal, which is, in turn, driven mainly by the performance versus segmentation and the cost of achieving a given segmentation.* More detailed factors are listed below:

Performance criteria:
1) MIP Efficiency/pad
2) Hit multiplicity/MIP
3) Uniformity of response across active layers
4) Need for or ease of calibration
5) Recovery time after hit(s)
6) Recovery time after a "significant beam event"
7) Rate of discharges (gas)
8) Track-cluster separability
9) PFA jet resolution at a) Z-pole, b) 250, 500, 1000 GeV

10) Magnetic field issues – signal location offsets in barrel and endcaps (gas)
11) Response to neutrons

Technology issues:
1) Maturity and previous history
2) Reliability
3) Availability of components (in quantity)
4) Active layer thickness
5) Smallest readout unit size
6) Technical risk of approach
7) Ease of assembly/testing/installation/commissioning (often referred to as “scalability”).
8) Effects of aging on performance

Cost:
1) Overall HCal cost
2) Active layer cost as a percentage of total cost
3) System development costs
4) Costs for assembly and test

Steps Forward

There is potentially a conflict between the time required for building and testing HCal prototypes and the schedule for the CDR. However the various phases of development identified below should be as coherent as possible with the CDR and EDR dates:

1) Initial prototyping and basic measurements of efficiency, hit multiplicity, operational robustness, etc. on small scale systems. This has largely been completed and each technology options will be asked to prepare a report on this, for management consideration before moving on to large prototypes.

   Schedule: Reports addressing the performance criteria and technological issues by end of April 2007

2) Development of high density readout and operation of a number of active layers in a stack to establish scalability and some level of comparison with shower simulations for single particles. This includes the "Slice Test" of RPC/GEM at Fermilab in Spring 2007, and elements of the CALICE HCal stack tests at CERN in 2006/7. The successful operation of the detector modules for these tests provides some information on reliability and robustness. The tests of the CALICE scintillator/SiPM stack using single incident particle data will provide the first comparison with GEANT4 simulations. To a limited extent, similar information will be available from the RPC/GEM Slice Test also. For the scintillator HCal option, the issue of high density readout requires the development of direct SiPM-on scintillator-tile configurations and the associated electronics board

   Schedule: Some GEM/RPC Slice Test results, and comparisons of the scintillator HCal results with simulations, may be available before LCWS07 in DESY, at the end of May 2007, when the ILC Calorimeter R&D review will take place. Initial results from trials of scintillator tile readout using directly coupled SiPM's should be available on the same timescale. However, the full results are not expected until later in 2007.

3) The results from phases 1) and 2) on stack operations, electronic readout implementations and scalability, simulation comparisons, and cost should then be evaluated before proceeding with larger scale prototypes. (Note that for all three technologies these two steps have not fully proceeded in the same order. For instance RPCs and GEMs have already demonstrated reasonable scalability but have not been tested in large numbers. On the other hand a scintillator-SiPM stack has seen beam but scalability is not yet demonstrated.)

   Schedule: An SiD meeting to evaluate the results of the ILC Calorimeter review should be scheduled for late 2007. The technical results, performance data (energy resolution, simulation comparisons,…), and availability of significant funding, should all be input to decisions on which large prototypes to pursue. *The goal will be to establish the next phase of the SiD calorimeter development to deliver the necessary input to enable a unique choice of HCal technology, or leading candidate plus alternate(s), to be made for the CDR.* The period available for this next phase will be approximately one year. The various technology options are described below in Step 4.

Given the FY07 funding situation, and the probability that the priority/supplemental LCDRD funding will not be available, the strategy for FY08 will need to be re-evaluated during the proposed late 2007 SiD meeting described above.

In parallel, the results from complete PFA's will be evaluated for positive/negative implications for each active layer technology. The results to this point should all be available prior to writing the SiD CDR.

Schedule: A comprehensive review of simulation and PFA results impacting the SiD HCal will be carried out in Fall 2007 in parallel with the hardware/performance review just described. It is acknowledged that, since the supplemental funding required for Step 4. below may not be forthcoming, decisions for technical choice(s) to be included in the SiD CDR may be based solely on simulation/PFA and small or partial prototype results.

4) If a unique choice of technology is possible after phase 3), and the required funding is available, then a full size ($1m^3$) stack or even a partial ILC prototype using this technology should be built and tested as soon as possible to verify performance for inclusion in the SiD CDR. The decision should be based on the performance criteria and be carried out as a review under the direction of the SiD management as described in 3). Mechanisms for this decision should be developed well beforehand to ensure transparency. If a unique choice is not possible and issues remain, then two or more large stacks or prototypes should be built and tested for performance and direct comparisons. Possibilities for these stacks include:
    a) $1m^3$ RPC stack with 1 x 1 cm^2 pads and high density front end readout (DCAL)
    b) $1m^3$ GEM stack with 1 x 1 cm^2 pads and high density front end readout (DCAL or KPiX)
    c) $1m^3$ scintillator stack with tiles smaller than 3 x 3 cm^2, and/or on board high density readout (KPIX or other ASICs. This will be a second generation prototype so some emphasis on this as an ILC prototype may be appropriate.
    d) $1m^3$ Micromegas stack with 1 x 1 cm^2 pads and high density front end readout (French chip?)

If this step is necessary, it is clearly desirable that the stacks and/or an ILC prototype be built and tested *as soon possible*.

Schedule: A second comprehensive review of SiD Calorimetry should be scheduled for mid-2008 to make decisions, as required, for the inclusion of technology choice in the SiD CDR, and the further module construction to be carried out over the period of writing the EDR.

Goals for the $1m^3$ stack Test(s):

a) Large scale tests of technologies
   - If gas, stability of gas calorimeter systems with large channel count.
   - Rate of discharges, associated damage/recoverability
   - Uniformity of response across planes, plane-to-plane
   - Stability of response over a ten day period
   - Noise rate vs. threshold as measured by number of active channels during no beam conditions or away from an identified muon.

b) Test of traditional calorimetry performance over a range of energies and species(to ensure we at least have a rationale basis for comparison w/o the confusion inherent with PFA and the ever present claim that it can be optimized.)
   - Single particle energy resolution with fixed sampling fractions
   - Pion rejection/efficiency with respect to electron ID (for tracks partially showering in the HCal).

c) Study of shower shape and verification of simulations (needed to really trust PFAs)
   - Shower shapes vs. particle type and beam energies
      i. Average shower depth starting point
      ii. Average shower width vs. depth
      iii. Moments of transverse energy depositions
      iv. Hits/layer within cone
      v. Hits/layer in rings outside cone
      vi. Longitudinal shower profiles
      vii. Hits vs. energy for each particle type

- Effects of threshold selection(s)

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d) Tests of PFA components (cluster forming/connecting, topological associations,..)
    - PFA response at fixed energies.
    - An open issue that will require study is the degree of agreement required between data and simulations. This may entail a determination as to how well the simulations must be “tuned” to achieve agreement for all particle types?

5) Once a choice has been made (unique or leading candidate) for the CDR, then this technology will be subjected to further extensive testing during the 2-3 year period of writing the EDR. The goal will be to provide the input for a complete HCal and overall SiD calorimeter system designs for the final EDR.

Implications for Simulation and PFA development.

For whichever stacks, or partial stacks, are to be exposed to beam, we must have detailed simulations that provide the items for data/simulation comparison described in section 4 c) above. This should include all possible beam particle types, anticipated energies, and incident angles.

Since a major driver for the technology choice is performance vs. segmentation, there is an urgent need to move the simulation work on to higher center of mass energies up to 1 TeV. Until we understand the segmentation requirements from jets at the higher energies, we cannot make progress in addressing the issue of fine segmentation for each technology. A critical part of the SiD CDR, but especially the EDR, will be to offer convincing evidence that we can achieve the required jet energy and jet-jet mass resolutions over the complete range of energies for the ILC via PFA, and that we have one or more HCal technology choice(s) that can deliver the required input to the PFA.

Schedule: PFA development should concentrate on physics processes at 500 GeV CM. A recommended program starts with the process e+e- -> ZH where Z -> ll and H -> dijet at 500 GeV. This lets the PFA performance be obtained on ~120 GeV jets – where it must be used most. Starting with only

2 jets with an unambiguous mass shows only PFA performance without adding jet combination confusion. The next step is to include the hadronic decays of the Z – now 4 jets with the same jet energies, but filling up more of the detector. At this point, PFA performance can be used to optimize some detector parameters, e.g., IR of ECAL, CAL granularity, B-field. Also, the PFA performance can be evaluated in terms of fraction of branching ratio to hadrons that can be used in analysis – the PFA goal can be cast in useable luminosity instead of jet E resolution. Then, the next process to be investigated should be e+e- -> tt - lower E jets, but 6 of them. The PFA performance should not be compromised at this stage. Lastly, one could try e+e- -> qq at 500 Gev to get 250 GeV jets. These should be very challenging for PFA, but not too useful for e+e- physics analyses. We would not include Z-Pole in the document, but would continue to use it as a tool for development, comparisons, etc. We think this program is possible this year, especially with the recent release of the PFA template.

Engineering Studies

Since SiD will be in a competitive situation on the CDR's with respect to other concepts, a first-level of engineering studies must be completed in the next 12 months. Since the thickness of the active gaps for all technologies is expected to be in the range 7mm – 10mm, a first pass study for the HCal might use a generic value and steel absorber to get engineering activities underway. It is anticipated that this can begin early in 2007, once the first SLAC, FNAL, ANL SiD Engineering Group is in place. The areas that need consideration for the CDR are:

- Basic parameters of HCal module design (number of depth layers, absorber plate material and thickness, number of azimuthal divisions, number of barrel sections in z , design of endcap modules)
- FEA study of initial HCal structure
- Support of barrel, endcaps and solenoid
- Assembly procedure for barrel and endcaps.
- Magnetic force effects
- Effects on module sizes, support, of tungsten vs. steel.

Schedule: A first pass engineering study should be available by the end of calendar 2007, to allow studies of subsystem variations while the CDR is prepared.