Progress Report from CALICE

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ON BEHALF OF THE CALICE COLLABORATION

The CALICE collaboration develops calorimeters for the ILC detectors. This report summarizes recent progress with special emphasis on test beam results. The slides of the talk can be downloaded from [1].

1 The CALICE collaboration

The CALICE collaboration [2] currently counts over 200 physicists and engineers from twelve countries located in all three regions of the physics world. The collaboration formed with the aim of developing and testing various calorimeter technologies for use in ILC detectors. The CALICE calorimeters are optimized for the application of Particle Flow Algorithms (PFAs) [3] and so feature high segmentation of the readout, both longitudinally and laterally.

The collaboration builds so-called *physics prototypes* and *technical prototypes*. The physics prototypes are based on various technologies (silicon, scintillator, RPCs, etc.) and usually are large enough to contain most of the electromagnetic (in the case of electromagnetic calorimeters) and hadronic showers (in the case of hadronic calorimeters). They are not necessarily optimized for use in an ILC detector, but nevertheless undergo a detailed test program in particle beams. The major purpose of these physics prototypes is to provide a basis for choosing a viable calorimeter technology for the ILC detectors, to measure electromagnetic and hadronic showers with unprecedented spatial resolution (these measurements are needed to validate the simulation of hadronic showers, a crucial requirement for the development of a detector optimized for PFAs), and to advanced calorimeter technologies and understanding of calorimetry in general.

On the other hand technical prototypes, even though perhaps smaller or only partially equipped, are designed such that in principle they could be inserted into and operated within an ILC detector. Issues of the high/low voltage distributions, possibly the gas supply, and the data collection routes are being addressed with the boundary conditions of a real detector in mind.

Table I provides an overview of the various projects currently being pursued by the collaboration. Some projects, such as the silicon tungsten electromagnetic calorimeter (ECAL), are well advanced, others, such as the MAPS-tungsten effort, have only been initiated recently. The developments are tightly related to the three ILC detector concepts which are optimized for PFA performance, namely GLD, LDC and SiD. In the following we

will mainly concentrate on the projects which have already undergone tests in particle beams or are almost ready to do so.
The collaboration tested prototype modules in various test beams over the past 18 months:

- at DESY (electrons of 1 – 6 GeV)
- at CERN (electrons and pions of 6 – 120 GeV) and
- at FNAL (protons at 120 GeV).

At CERN alone the collaboration collected over 60 million events. Some of the results of this effort will be presented in the following. The protons at FNAL were used to test single layers of RPCs and GEMs.

Table I. Overview of current CALICE projects and their status

Calorimeter	**Technology**	**Detector R&D**	**Physics Prototype**	**Technical Prototype**
ECALs	Silicon - Tungsten	Well advanced	Exposed to beam	Design started
	MAPS - Tungsten	Started		
	Scintillator - Lead	Well advanced	Exposed to beam	
HCALs	Scintillator - Steel	Well advanced	Exposed to beam	Design started
	RPCs - Steel	Well advanced	Almost ready to be build	(Design started)
	GEMs- Steel	Ongoing		
	MicroMegas - Steel	Started		
TCMTs	Scintillator - Steel	Well advanced	Exposed to beam	

Being part of a larger collaboration, such as CALICE, offers significant advantages to the various efforts within the collaboration. For instance, different projects share the same readout system (such as the Si-tungsten ECAL and the scintillator-steel HCAL). All projects use the same data acquisition software, which facilitates combined tests of electromagnetic and hadronic calorimeter prototypes. The same test beam is often shared by different groups which results in mutual help with the setup of the equipment and the understanding of the beam lines. Last but not least, the CALICE collaboration offers a convenient forum to discuss ideas, present results and compare performances. Additional details on the collaboration and its various projects can be found in the CALICE report to the 2007 ILC calorimeter review [4].

2 Silicon-Tungsten electromagnetic calorimeter

A Silicon-tungsten ECAL offers the possibility of fine readout segmentation together with a small Molière radius (of the order of 1.0 to 2.0 cm). Within the paradigm of PFAs, the latter is crucial for the identification and measurement of electromagnetic showers. A physics prototype consisting of 30 layers has been assembled. The tungsten plates vary in thickness from 1.4 mm (or 2/5 X_0) for the first 10 layers, to 2.8 mm (4/5 X_0) in the middle section and 4.2 mm (6/5 X_0) for the last 10 layers of the module. The readout area measured 12 x 18 cm^2 per plane and featured 1 x 1 cm^2 pads. The entire prototype module counted 6480 readout channels. The electronic front-end boards were placed on the side of the module, with digitization taking place in a VME-based system located off the detector.

Detailed measurements of the response to electrons were performed in the DESY and CERN test beams. Figure 1 shows the measured energy versus the nominal beam energy. The response is seen to be linear within the 1% level.

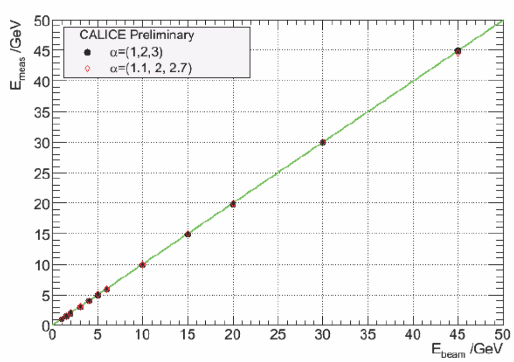

Figure 1: Silicon ECAL: Reconstructed energy versus beam energy

The energy resolution as function of $1/\sqrt{E_{beam}}$ energy is shown in Fig. 2. The open and closed circles correspond to different weighting schemes for the three sections of the calorimeter. The resolution can be parameterized as 17.1%/$\sqrt{E}$ with a small constant term of 0.5%. The results are very well reproduced by Monte Carlo simulations based on GEANT4.

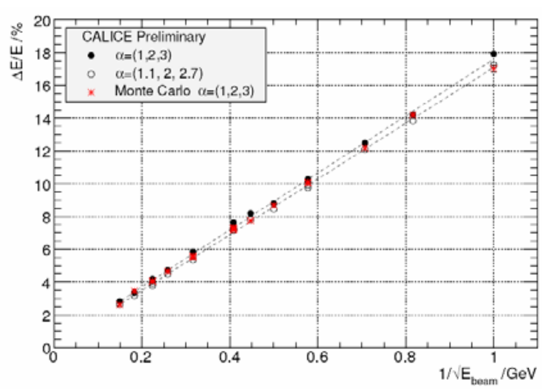

Figure 2: Silicon ECAL: Energy resolution versus $1/\sqrt{E_{beam}}$

Figure 3 shows the average radius for 90 and 95% energy containment as a function of beam energy. The Molière radius, defined as the radius corresponding to 90% energy containment, is of the order of 20 mm. This value is approximately a factor 2 larger than the Moliere radius of a solid block of tungsten without gaps for the active elements.

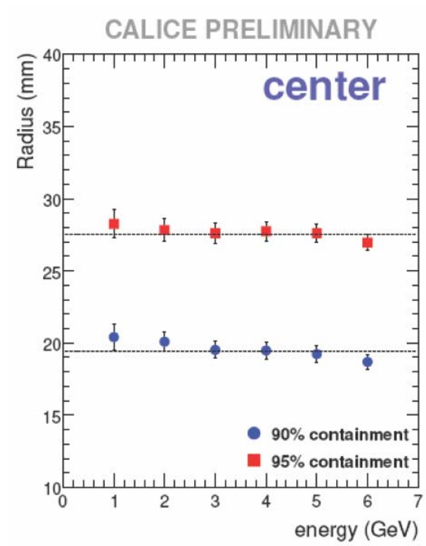

Figure 3: Silicon ECAL: Radius for 90% and 95% energy containment for electrons

3 Scintillator-Tungsten electromagnetic calorimeter

Scintillator as active element is being pursued by both an ECAL and an HCAL group. The advent of Silicon Photomultipliers [5] makes the development of a detector with small scintillator tiles to be operated in a strong magnetic field possible. The ECAL group built a prototype calorimeter with 26 active layers interleaved with 1 X_0 Tungsten plates. The scintillator tiles measure 4.5 x 1.0 x 0.3 cm^3 each. The setup tested different configurations for the light collection and tile separation: a) using wavelength shifting fibers imbedded in tiles separated by machined groves, b) using the same scintillator tiles without wavelength shifting fibers (direct coupling), and c) using wavelength shifting fibers imbedded in extruded scintillator tiles. The light was collected with Hamamatsu Multipixel Photon Counters (MPPCs).

The prototype calorimeter was tested in the DESY electron beam. Figure 4 shows the measured energy resolution versus $1/\sqrt{E_{beam}}$. The results can be parameterized as

$$\sigma/E = 13.45\%/\sqrt{E} + 2.87\% \text{ (added in quadrature)}$$

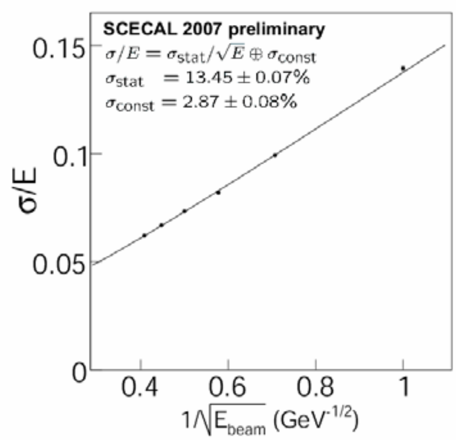

Figure 4: Scintillator ECAL: Energy resolution versus $1/\sqrt{E_{beam}}$ for electrons

4 The ultimate digital calorimeter: MAPS

The third ECAL project investigates the use of Monolithic Active Pixel Sensors (MAPS) as active elements. Here the comparator and logic is imbedded into the sensor structure. Due to the large number of channels (10^{12} pixels for the ECAL of an ILC detector), the readout resolution is reduced to a single bit (digital readout). A first prototype sensor with 50 x 50 μm^2 pixels has been designed and is being prototyped.

5 Scintillator-Steel hadron calorimeter

A (almost complete) physics prototype calorimeter using scintillator pads as active elements interleaved with 20 mm thick steel plates was exposed to both the DESY and CERN test beams in 2006. The tiles measure 3 x 3 cm^2 in the center of a given plane, increase to 6 x 6 cm^2 and finally 12 x 12 cm^2 at the edge of the planes, see Fig. 5 for a photograph of one of the layers. The area of each layer is approximately 1 m^2. The completed module with 38 layers will feature of the order of 8,000 readout channels, each individually equipped with a Silicon-Photomultiplier (SiPM). The readout utilizes a VME based data acquisition system, located off the detector, similarly to the system used by the Silicon-Tungsten ECAL. In the 2006 test beam run 23 of the planed 38 layers were fully equipped.

A detailed calibration procedure, involving LEDs and muon beams has been developed. Corrections for light-yield non-uniformities, SiPM gain variations, SiPM non-linearities in the response, and non-uniformities in the readout electronics are being applied. The light yield is found to be very satisfactory, with an average of 16 pixels per tile per minimum ionizing particle.

Standalone data (without ECAL in front of the module) have been collected with both electrons and pions. The analysis of the electron data is particularly difficult due to the higher sensitivity to the non-linearity of SiPMs. In this case some deviations to Monte Carlo expectations are observed, possibly due to non-optimal corrections to the non-linearity and/or additional dead material in front of the module which has not yet been included in the simulation. This is work in progress.

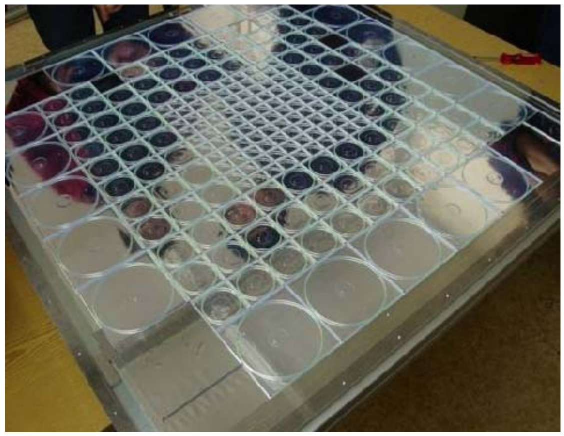

Figure 5: Scintillator HCAL: Photograph of one detector plane

Figure 6 shows the response and resolution as function of pion beam energy. The results are compared with two different predictions based on the GEANT3 simulation code, one based on GEISHA and the other one using FLUKA. Significant deviations to the measurements and among the predictions are observed. It should be noted that these measurements used an incompletely equipped module and that the final results using the complete module are expected to be significantly better.

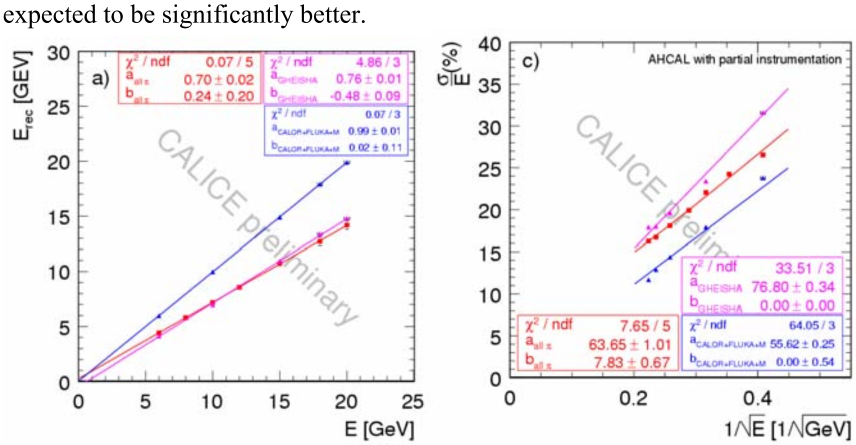

Figure 6: Scintillator HCAL: a) Reconstructed energy versus beam energy; b) Energy resolution versus $1/\sqrt{E_{beam}}$

Figure 7 shows a first measurement of the transverse shower shape for different incident pion energies (between 6 and 20 GeV). Comparisons with simulations are forthcoming.

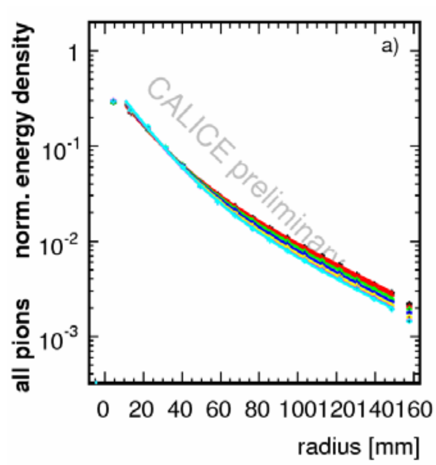

Figure 7: Scintillator HCAL: Measurement of the transverse shape of pion showers

6 Tail catcher and muon tracker

The purpose of the Tail Catcher and Muon Tracker (TCMT) is to provide a precision measurement of the longitudinal tails of hadronic showers. In the CERN test beam run it was located behind the ECAL and HCAL modules, as shown in Fig. 8. The TCMT consists of 16 active layers, each with an area of 1 m^2. The readout planes are subdivided into strips of scintillator with the dimensions of 5 x 100 x 0.5 cm^3. Each strip is read out individually by a Si-PM. The electronic readout system is identical to the one used for the other prototype calorimeters using scintillator as active element.

The TCMT was completed in 2006 and participated in all test beam runs at CERN. First results show a strong anti-correlation between the energy measured in the HCAL and the energy leaking into and measured by the TCMT. Adding the TCMT energy to the one measured in the calorimeter(s) located in front, significantly improves the overall energy resolution.

7 Digital hadron calorimeter

Last but not least, the CALICE collaboration investigates the use of gaseous detectors as active elements of a finely segmented hadron calorimeter. Within the collaboration different subgroups explore the use of Resistive Plate Chambers (R&D almost complete), Gas Electron

Multipliers (R&D ongoing) and Micromegas (R&D recently initiated). These detectors are being read out with 1 x 1 cm^2 pads, leading to a large overall number of readout channels. Equipping the same 38 layers of the scintillator HCAL with these devises results in a channel count of close to 400,000. To simplify the readout system, the resolution per pad has been degraded to a single-bit (digital) readout. Monte Carlo simulations indicate that such a digital readout of small pads is able to provide an adequate single-particle energy resolution.

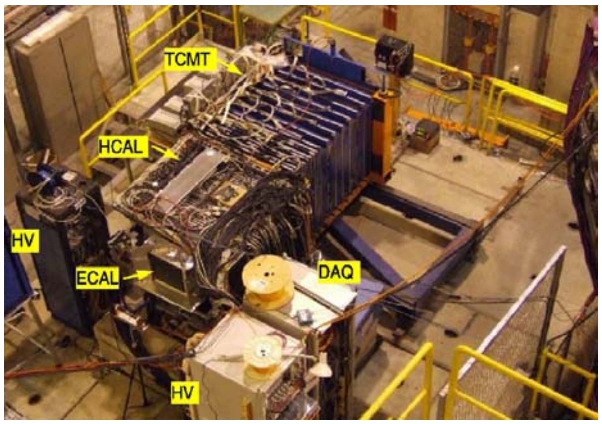

Figure 8: TCMT: Photograph of the setup in the CERN beam

A large effort has been deployed to develop an economical readout system capable of handling the inherently large number of channels of this type of calorimeter. The system is based on a front-end ASIC located directly on the pad-board and reading out 64 individual pads. The readout chain is completed with data concentrator (1 per 4 ASICs) and data collector (1 per 12 data concentrators) modules. A vertical slice of the readout system is being assembled as a proof of principle of the concept. Figure 9 shows the top of the prototype pad board, including four front-end ASICs.

At the time of the conference the first 1,000 cosmic ray events had been collected using the complete readout chain. The group is now preparing a larger test (involving up to 10 RPCs and 2 GEMs) in the Fermilab test beam.

8 Towards technical prototypes

In parallel to the construction and data taking with the various physics prototypes, the collaboration actively pursues the next steps towards 'realistic' calorimeter modules, the so-called technical prototypes. In the following we list a few selected topics of research.

The next step for the scintillator-tungsten ECAL features a compact design of the layer structure with imbedded front-end electronics. Particular care is devoted to keeping the active gap size as small as possible, in an effort to retain the small Molière radius of Tungsten. A number of issues, such as electronics cooling, wafer gluing, and production techniques, are being addressed.

Figure 9: Gaseous HCAL: Photograph of a pad board equipped with 4 ASICs

The scintillator ECAL and HCAL are investigating the possibility of direct coupling to the SiPM or MPPC (omitting the wavelength shifting fiber). Ways to obtain a uniform response as function of the position on the tile are being developed. First designs of an integrated readout system, located inside the active gap, are being evaluated.

The next step in the development of the front-end electronics includes on-detector digitization (apart from the gaseous HCAL, which already includes this feature), token ring readout of the front-end ASICs, and possibly power pulsing. The latter will lead to a significant reduction in overall power consumption and therefore to a drastic simplification of the cooling system.

9 Conclusions

To conclude Table II summarizes the current plans for test beam activities until the end of 2009. The test beam program at CERN will conclude in 2007, after which the equipment will be moved to Fermilab in late 2007/early 2008.

10 Acknowledgements

The author likes to thank all members of the CALICE collaboration for their generous help in preparing the talk and this document.

Table II: CALICE test beam plans

Project		**2007b**	**2008a**	**2008b**	**2009a**	**2009b**
Si-W	ECAL	CERN test beam	FNAL test beam			
MAPS		1^{st} prototype chip		2^{nd} prototype chip	DESY test beam	
Scintillator				FNAL test beam		
Scintillator	HCAL	CERN test beam	FNAL test beam			
RPC		Vertical slice test in FNAL test beam	Physics prototype construction	FNAL test beam		
GEM		Vertical slice test in FNAL test beam	Further R&D on GEMs		Physics prototype construction	FNAL test beam
Micromegas			1 plane			
Scintillator	TCMT	CERN test beam	FNAL test beam			

11 References

[1] Slides: http://ilcagenda.linearcollider.org/contributionDisplay.py?contribId=10&sessionId=1&confId=1296

[2] Web site of the CALICE collaboration: http://polywww.in2p3.fr/activites/physique/flc/calice.html

[3] For more information on PFAs, consult talks given in the PFA session of this conference.

[4] http://www-flc.desy.de/lcnotes/notes/LC-DET-2007-007.pdf

[5] For more information on Silicon-Photomultipliers (Si-PMs) or Multipixel-Photoncounters (MPPCs), consult the talks given in the *Photosensor* session of the calorimeter parallel sessions.