PROCEEDINGS OF SCIENCE

Performance of the CALICE calorimeters

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Most of the important physics processes to be studied at a future e^+e^- linear collider have multi-jets in the final state. In order to achieve the best attainable jet energy resolution, a so-called particle flow measurement will be employed, and fine granular calorimeter is one of the key detector component for the particle flow. In this paper, test beam results of various calorimeter prototypes currently being developed by the CALICE collaboration will be presented.

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1. Introduction

The International Linear Collider (ILC) is a future energy-frontier electron-positron collider currently being designed by a world-wide collaboration. The physics goal of the ILC experiment ranges over a wide variety of processes in a wide energy region of center of mass energy. Most of the important physics processes to be studied in the ILC experiment have multi-jets in the final state, and therefore precise jet energy reconstruction plays an crucial role to the ILC physics. One of the performance goal required to the ILC detector is the jet energy resolution of $\sigma_E/E = 30\%/\sqrt{E(\text{GeV})}$ which is a factor two better than the best jet energy resolution achieved at LEP. Achieving jet energy resolution of $\sigma_E/E = 30\%/\sqrt{E(\text{GeV})}$ is rather technical challenge for the ILC detector. Such energy resolution could be achieved by a combination of highly efficient and nearly hermetic tracking system with a very fine transverse and longitudinal segmented calorimeters. The calorimeters are located inside the magnet, so compactness is also important issue for them. Since the momentum resolution for the charged particle measured by the tracking system is much better than the energy resolution of the calorimeters, the best jet energy resolution is obtained by reconstructing momenta of individual particles avoiding double counting among trackers and calorimeters; charged particles, whose energy fraction in a jet is about 60%, are measured by the trackers, photons, whose energy fraction is about 30%, are measured by electromagnetic calorimeter (ECAL) and neutral hadrons, which carry the rest of energy, are measured by both ECAL and hadron calorimeter (HCAL). This is known as a particle flow measurement[1]. In the particle flow, separation of particles in the calorimeters is crucial, and highly granular calorimeters are therefore essential in the ILC detector.

CALICE is a collaboration of the Calorimeter R&D for a future linear collider. Currently, there are more than 330 physicists and engineers from 57 institutes and 17 countries. Final goal of the CALICE collaboration is to construct fine granular calorimeter which is optimized for the particle flow measurement of the multi-jets final state, and near term goal is to built the prototype calorimeters in order to establish the technology, and collect hadronic showers data to tune the clustering algorithm and validate existing MC models. There are a number of calorimeter technologies for the linear collider detector as summarized in Table 1, and all calorimeters are designed for the particle flow - i.e. fine granular. A number of test beams have been carried out since 2006 by the CALICE collaboration with various prototype modules. Left figure of Figure 1 shows the history of data taking. A lot of data have been already taken with the various combination of the ECAL and HCAL prototype modules. Although the test beam results of each prototype module will be

Table 1: Summary of the calorimeter technologies.

Type	ECAL			HCAL			
Absorber Layer	Tungsten			Tungsten/Iron			
Readout	Analog		Digital	Analog	(Semi)Digital		
Sensitive Layer	Silicon	Scintillator Strip	MAPS	Scintillator Tile	RPC	GEM	Micromegas

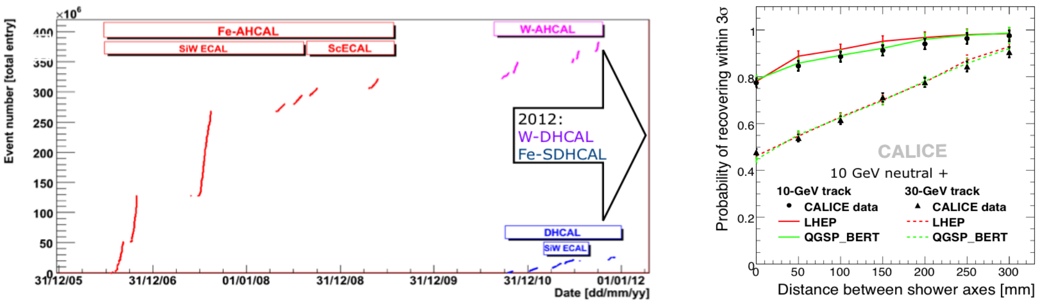

Figure 1: Test beam data taking summary performed by the CALICE collaboration (left) and probability of two particle separation as a function of the distance between two hadronic showers (right).

described in the following sections, here a highlight of the test beam result will be shown in the rest of this section. We have demonstrated two particle separation using the Silicon-tungsten(SiW) ECAL and Scintillator Analog HCAL (AHCAL). Right figure of Figure 1 shows probability of a two particle separation as a function of the distance between two hadronic showers. As can be seen from the figure, the resolution degrades as the second particle comes closer. The figure also shows the MC data well reproduces the test beam data. From this result, we can say the particle flow concept works very well with the fine granular calorimeters. More detailed analysis can be found in [2].

2. Electromagnetic Calorimeter (ECAL)

2.1 Silicon ECAL

A prototype module with the silicon sensor as sensitive layer and tungsten as absorber layer has been constructed. In total, there are 30 layers which is correspond to 24 X_0 and one λ_I. The silicon sensor of the prototype module was segmented to 1cm $\times$ 1cm cell. Test of new silicon sensor, whose cell size is 5mm $\times$ 5mm, is now on-going at Ecole Polytechnique and Kyushu University. Schematic of the prototype module together with the silicon sensor is shown in Figure 2. Test beam was performed from 2006 to 2008 with this module at DESY, CERN and FNAL. Electrons and pions with various energies were injected to the module. These data are very fruitful for validation of the GEANT4 models. We found that the QGSP_BERT physics list reproduces the data well especially for higher energies. More detailed results can be found in [3].

2.2 Scintillator Strip ECAL

The scintillator-strip with Multi-pixel photon counter (MPPC) is another option for the sensitive layer of the ECAL. The scintillator size is $45 \times 5 \times 2$ mm^3 and MPPC size is $1.4 \times 1.4 \times 0.6$ mm^3. Scintillator strips in odd layers are orthogonal with respect to those in even layers in order to realize the 5mm $\times$ 5mm effective granularity. We can expect a cost reduction compared to the silicon ECAL, however, special software algorithm to extract the effective lateral granularity from the strip structure should be developed. Test beam with the prototype modules was also performed since 2007 for the scintillator ECAL. Figure 3 show preliminary results obtained from electron data

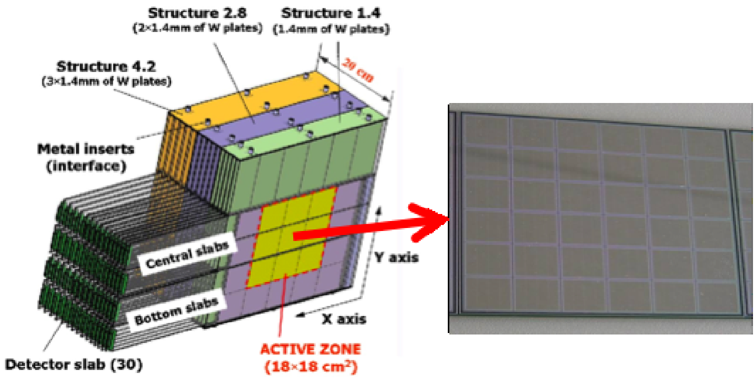

Figure 2: Schematic view of the silicon ECAL together with silicon sensor.

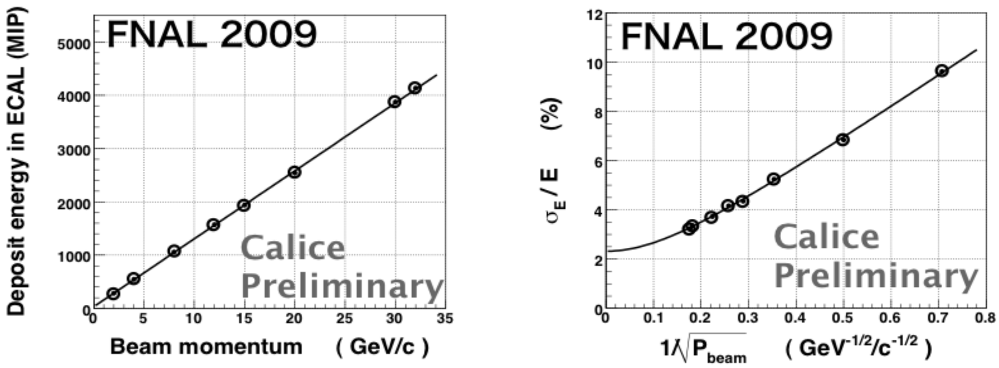

Figure 3: Preliminary results of the performance of the scintillator strip ECAL.

taken in 2009 at FNAL. The linearity deviation is obtained to be less than 1.5%, and the stochastic term and constant term of the energy resolution was evaluated to be $(13.16 \pm 0.05\%)/\sqrt{E(\mathrm{GeV})}$ and $2.32 \pm 0.02\%$, respectively.

3. Hadron Calorimeter (HCAL)

3.1 Analog HCAL

A prototype module of the analog HCAL has been also constructed and tested. The prototype module consist of 212 scintillator tiles whose size is 3×3 cm^2 in one sensitive layer, and WLS fiber and SiPM are used for readout. Total number of layer is 38 and iron is used for absorber layer. Test beam was performed from 2006 to 2011, and we found excellent electromagnetic performance. The calorimeter is non-compensating, but high granularity can be used to distinguish the electromagnetic and hadronic energy deposit in the calorimeter. If we apply the software compensation, the stochastic term of the energy resolution was improved from $57.6\%/\sqrt{E(\mathrm{GeV})}$ to $45\%/\sqrt{E(\mathrm{GeV})}$ as shown in the left figure of Figure 4, while good linearity was maintained.

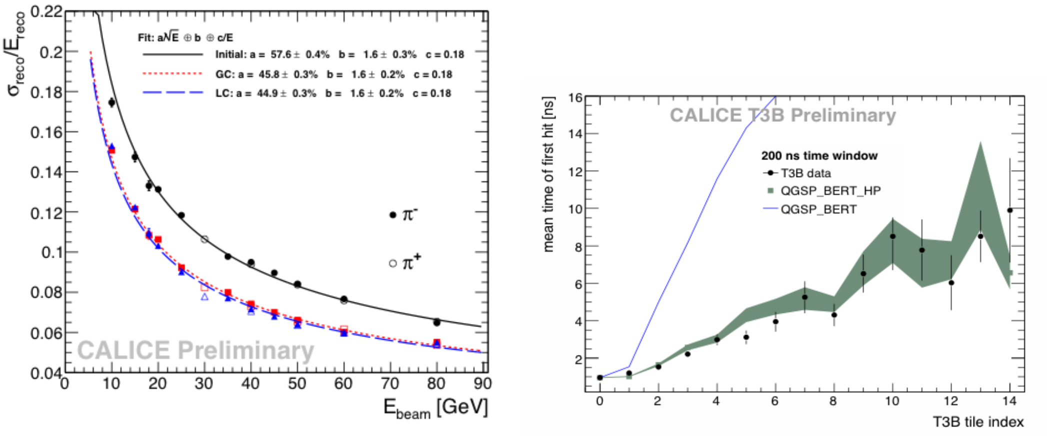

Figure 4: Effect of the software compensation (left) and preliminary result from the T3B experiment.

T3B is a first dedicated experiment to study the time structure of hadronic shower for the CLIC HCAL. Fifteen 3cm $\times$ 3cm scintillator cells were installed downstream of the analog HCAL to study the radial extent of the hadronic shower. Notice that the absorber of the HCAL is not iron but tungsten in this case. We found that data is consistent with the QGSP_BERT_HP model as shown in the right figure of Figure 4.

3.2 Digital HCAL

We also have a digital readout option instead of the analog readout. Digital calorimeter has even finer granularity, 1×1 cm^2, than analog calorimeter, and binary readout is enough due to the large number of cells in such case. We have two options for the sensitive layer; RPC based and GEM based. A prototype of the RPC based digital HCAL has been constructed. RPC layers are inserted in the existing CALICE analog HCAL. The number of channels is 480 thousand and this number is world record. Left figure of Figure 5 shows the energy resolution for pions of the digital HCAL. Red line shows the resolution with standard pion selection and blue line shows that with requiring no shower leakage.

For the GEM-based digital HCAL, test beam was also carried out with the 30×20 cm^2 chambers in August 2011. Right figure of Figure 5 shows an event display of the prototype module of the GEM-based digital HCAL. Analysis of the test beam data is currently on-going.

3.3 Semi-digital HCAL

As described in the previous section, good energy resolution can be achieved by the single-bit digital calorimeter. However, the shower core will be very dense at high energy, and saturation will occur. In this case, two-bits readout can improve the performance. A calorimeter with this readout method is called as the semi-digital calorimeter. A prototype module of the semi-digital calorimeter with 48 GRPC sensitive layers has been constructed. The cross sectional area is 1m $\times$ 1m, the absorber layer is Iron and $6\lambda_I$ in total.

Another option for the sensitive layer of the semi-digital HCAL is micromegas. One layer prototype module has been also constructed, and tested in August 2011. In the next step, test beam

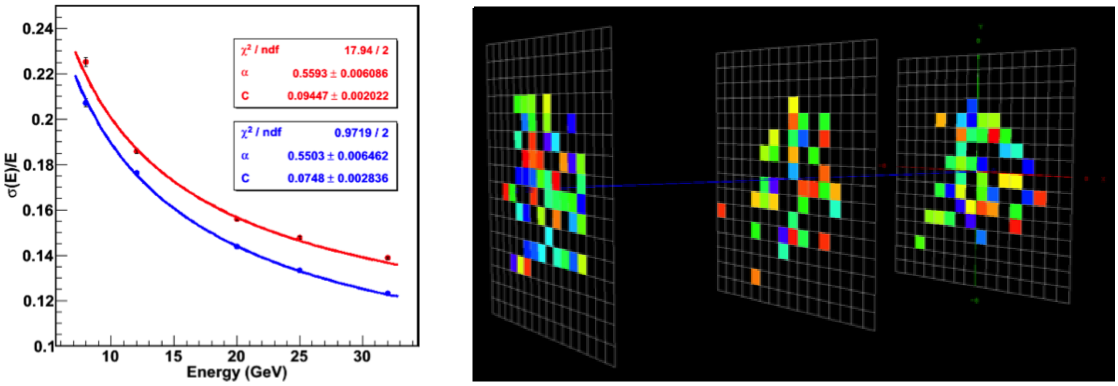

Figure 5: Energy resolution of the RPC-based digital HCAL (left) and an event display of the prototype module of the GEM-based digital HCAL.

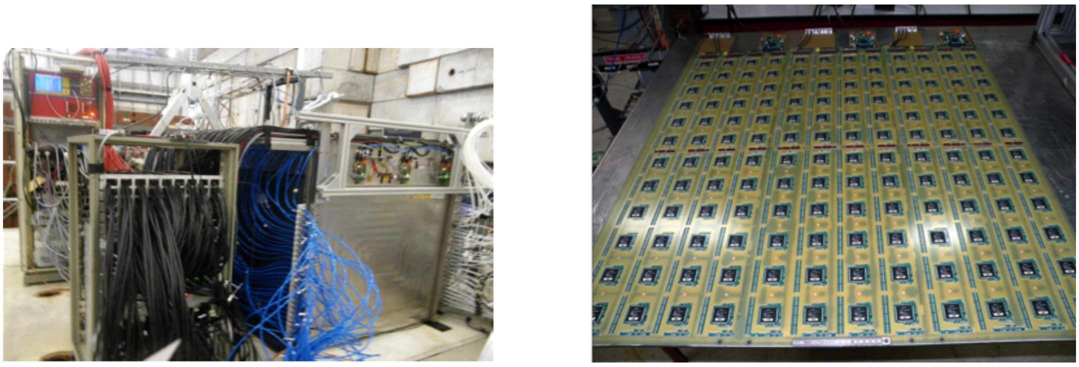

Figure 6: Pictures of the semi-digital HCAL prototype.

of 4 micromegas layers is expected with in this year. Pictures of each prototype module are shown in Figure 6.

4. Summary

The CALICE collaboration is aiming to establish highly granular calorimeter system optimized for the particle flow measurement of multi-jets final state at a future linear collider. Test beam campaign has been intensively carried out since 2006 in order to prove the principle of each calorimeter technologies. Excellent performances have been already shown from the test beam although some analyses are still on-going or just started. We will proceed to the technological prototype from the physics prototype as the next stage.

References

[1] M. A. Thomson, Nucl. Instrum. Meth. A 611, 25 (2009)

[2] The CALICE collaboration, JINST 6, P07005 (2011)

[3] The CALICE collaboration, JINST 5, P05007 (2010)