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CALICE results and future plans

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The CALICE collaboration is conducting an intensive R&D in the field of calorimetry with the aim to propose a new generation of calorimeters for the future linear collider experiments. Highly granular calorimeters based on the Particle Flow Algorithms (PFA) concept were conceived. Prototypes of this first generation of calorimeters were built and operated in test beams at DESY, CERN and FERMILAB. The results obtained from these tests provide valuable information on the structure of the hadronic showers. A second generation of calorimeters taking into account the integration aspects in the future experiments is being developed. The first prototypes of this generation are scheduled for 2011.

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1. Introduction

The PFA concept [1] is one of the most promising techniques to be used by the experiments of the future linear colliders to achieve unprecedented resolution in jet energy measurement. This is a crucial ingredient to understand the physics processes expected at the TeV-energy scale. The PFA relies on detector's capability to follow each particle in the different sub-detectors. To achieve this, the calorimeters should be endowed with a tracking capability which can be obtained by increasing their longitudinal and transverse segmentations. CALICE collaboration with its 337 scientists from 17 countries is strongly involved in the R&D of such calorimeters. The efforts which started in 2002 have led to the construction of first generation prototypes of highly segmented electromagnetic and hadronic calorimeters using state-of-the-art technologies. Those prototypes were exposed to beams at DESY, FERMILAB and CERN. The results obtained from these test beams proved the possibility of precisely measuring electromagnetic and hadronic particles energy and being at the same time able to separate close-by particles. The test beams allowed also to compare with the different models used in the simulation and to discriminate them. In parallel, CALICE collaboration is working on prototypes which take into account the integration problems of such calorimeters in the future linear collider experiments.

2. Physics prototypes

Two electromagnetic and two hadronic calorimeter prototypes with different detection technologies were built within the CALICE collaboration. A short description is provided here after.

2.1 Electromagnetic calorimeter prototypes

The first electromagnetic prototype called (Si-W) was built using silicon wafers as a sensitive medium [2]. The wafers of 500μm thickness were made of high resistivity silicon (5kΩ) and segmented into $1\times1\mathrm{cm}^2$ pads. 30 layers of $18\times18\mathrm{cm}^2$ were interleaved with tungsten plates of different thickness leading to <24 X_0 prototype. The choice of tungsten is due to its small Moliere radius (9mm), which helps with separating close-by electromagnetic particles. The ratio of signal to noise was measured to be 7.5. By exposing the prototype to electrons of different energies, the resolution was found to be $16.5/\sqrt{E} \oplus 1.1\%$ with a non-linearity less than 1% in the range between 6 and 45GeV. The second prototype (Sc-W)[3] was built using $4.5\times1\times0.3\mathrm{cm}^3$ scintillator strips as a sensitive medium. 72 strips were assembled to build each $(18\times18)\ \mathrm{cm}^2$ layer. 30 layers oriented alternatively in X and Y were built with the aim of reaching the equivalent of $1\mathrm{cm}^2$ granularity in the (X, Y) directions. The light produced by the passage of particles is collected thanks to a WLS fiber which runs along the strip. One of the two ends of this fiber is fixed on a $4\times3\mathrm{mm}^2$ MPPC device, and the same readout electronics used for the Si-W ECAL was used here. The absorber is also made of tungsten, but here the

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plates have all the same thickness (3.5mm each). Although the energy resolution obtained with this ECAL was found to be very good (15.15/√E⊕1.44%) the non-linearity (6%) was worse than expected. Work is ongoing to understand this behavior.

2.2 Hadronic calorimeter prototypes

The first hadronic calorimeter prototype (AHCAL)[4] was made with 38 layers of scintillator interleaved with 2cm steel plates (<5.3 λ_I) . Each layer is built of 324 squares of tile. The size of the 100 central tiles is 3×3cm^2 while the peripheral ones are slightly larger. As for the scintillator-based ECAL the light produced in each tile is collected through a WLS fiber and read out in analogue mode by a silicon photomultiplier (SiPM). In addition, the AHCAL is followed by 16 layers of 5×100cm^2 scintillator strips which form, with their 6 λ_I, a tail catcher of the hadronic showers not fully contained in the AHCAL. Pion beams were used to study the energy resolution. This was found to be (61.3/√E⊕2.54) %. However software compensation can be applied, which consists in reweighting the energy of the shower's dense part, which is most likely to be electromagnetic. The separation between electromagnetic and hadronic contributions, possible thanks to the AHCAL high granularity; leads to an important improvement in energy resolution (49.2/√E⊕2.34⊕0.504/E) %. A second hadronic calorimeter prototype (DHCAL) was recently completed. It uses GRPCs chambers as the sensitive medium [5]. Contrary to the AHCAL the readout electronics is digital. However the granularity is higher thanks to a lateral segmentation of 1cm^2 provided by an embedded electronics. 38 layers of 1m^2 were built. Each layer is made of a cassette containing 3 adjacent GRPCs of 3.1mm thickness each, which contains also the readout electronics boards. The layers were inserted in the same mechanical structure using the steel absorbers used for the AHCAL. The preliminary results obtained during a recent test beam at FERMILAB are very promising. A detailed analysis of the data collected is ongoing.

3. Results

The prototypes described in the previous section were exposed to electron, muon and pion beams in three different facilities; DESY, FERMILAB and CERN. An important result obtained from those test beams was to demonstrate the importance of high granularity on separating close-by particles. Electrons and photons separated by a distance as small as 5cm were unambiguously separated in both ECAL prototypes of CALICE as shown in figure 1. In the case of AHCAL, the overlay technique was used to study the separation of showers produced by charged and neutral particles. This was achieved by adding two showers created by two spatially close-by charged pions but belonging to different events after removing the track information of one of them to emulate a neutral hadron. The Pandora code [6] used for PFA studies was then applied to reconstruct the energy of the two showers. The difference between the true and the reconstructed energy of the showers was studied as a function of the separating distance. The results shown in figure 2 confirm the importance of high granularity in achieving

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a good separation of hadronic showers. Another important study conducted by the CALICE collaboration was the detailed study of hadronic shower behavior. This was obtained by analyzing data collected from the two ECAL and the AHCAL prototypes exposed to pions of different energies either separately or in combined configurations. These studies allow to discriminate among the different models of hadronic shower development used in the simulation by comparing the shape and the composition of the showers predicted by those models with those observed from data. An example is shown in figure 3 for the comparison of the longitudinal development of hadronic showers. The fine granularity of the calorimeters can be also a powerful tool to understand the composition of the hadronic showers in terms of their particle composition. This can be done by analyzing the shower profile since it depends on the nature of the shower constituents. Figure 4 shows a comparison between the data collected with the Si-W and two models which predict different particle composition of the showers.

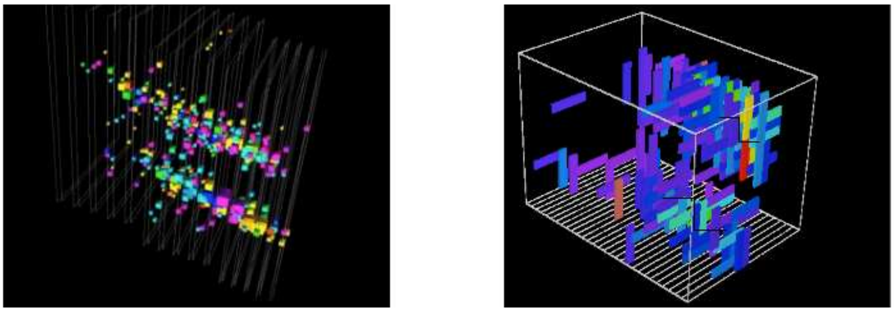

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Figure 1: A) 2 close-by electrons in the Si-W prototype, B) Two close-by photons in the Sc-W prototype.

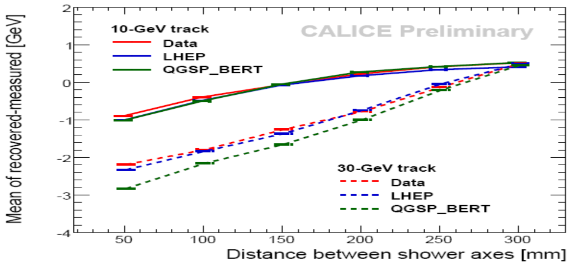

Figure 2: Separation of two 10GeV pions and two 30GeV ones in the AHCAL.

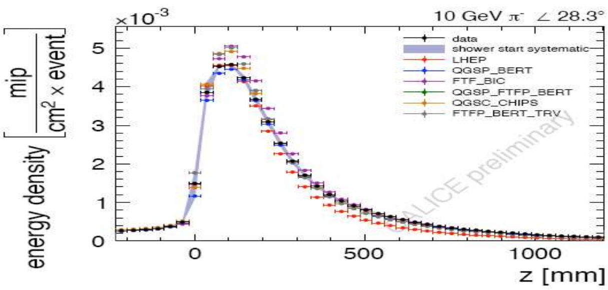

Figure 3: Longitudinal profile of 10GeV pions in a combined ECAL, AHCAL configuration.

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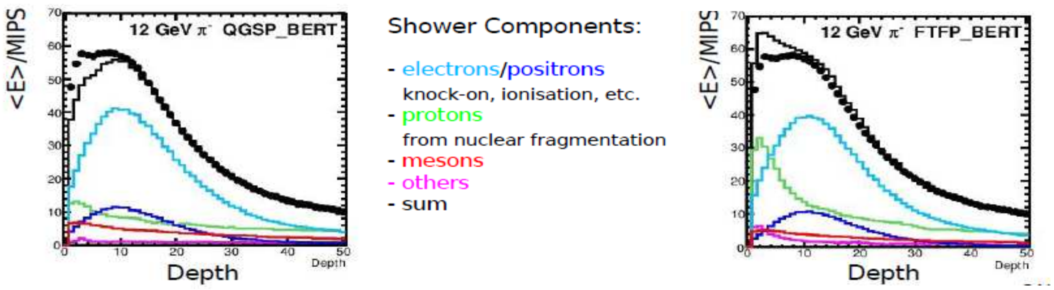


Figure 4: Comparison of 12GeV pions hadronic shower data content with two models: QGSP_BERT (left) and FTFP_BERT (right).

4. CALICE future plans

The success of the physics prototypes has allowed a new phase of development to be started, aiming at building prototypes addressing the technological aspects of the future linear collider experiments such as compactness, hermeticity and power consumption. In addition new technologies using new sensitive media were proposed for both the electromagnetic and the hadronic calorimeters. A brief description of the different developments follows.

4.1 Electromagnetic calorimeter developments

A technological (Si-W) prototype using a self-supporting mechanical structure built from the tungsten plates is under development. The first elements of this mechanical structure were successfully realized. The silicon wafers will be equipped with segmented guarding rings in order to reduce the cross-talk observed in the physics prototype. Its thickness will be also reduced to 300μm and will be read out by an embedded electronics. Tests are ongoing to build the first slab of such electronics. A complete mechanical prototype of $1.5\times0.55\times0.2m^3$ will be built and a tower of $30\times30cm^2$ section as well as a full long slab will be equipped with silicon wafers and the embedded readout electronics. The different services including the cooling system are also being developed and will be implemented in the technological prototype. Equivalent project with the Sc-W is foreseen in the near future. In addition to those two technologies, R&D is ongoing for a more granular but digital ECAL using MAPS. Different kinds of sensors were tested recently at CERN [7].

4.2 Hadronic calorimeter development

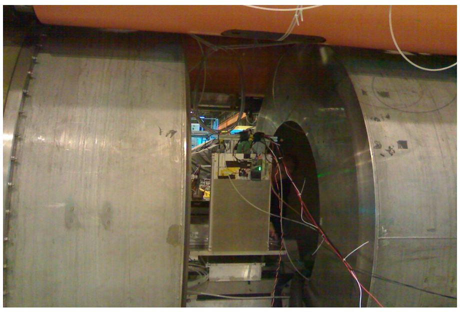
As for the case of the Si-W ECAL, a technological prototype was also conceived for the AHCAL. A self-supporting mechanical structure of $220\times110\times82cm^3$ is being built. Here also a tower and a full layer made of $3x3cm^2$ tiles, read out with embedded electronics are to be realized. A first slab hosting 4 ASICs of the new electronics was built and is being tested.

Another technological prototype called SDHCAL and using GRPCs is being built. The GRPCs here are $1\times1m^2$ in size. They are read out by an embedded electronics made of $1\times1m^2$

electronics board hosting 144 ASICs to readout the 1cm^2 pads. The electronics used here has 3 thresholds with the aim of having more information on the number of particles crossing each pad. The thickness of the sensitive medium including the detector and the electronics board is only 6mm [8]. This sensitive medium is inserted in a cassette made of two stainless steel walls. Dead zones in both the detector and the cassette were minimized. 48 cassettes will be built and inserted in a self-supporting modular mechanical structure made of stainless steel plates (>6 λ_I). Two of those cassettes were already built and tested in test beams at CERN. The prototype is expected to be completed in the first half of 2011. The prototype will host later cassettes of the same dimensions but with the GRPCs replaced by Micromegas. Indeed a parallel development is being followed in this direction [9] and a full cassette with the Micromegas bulk-based technology was built and tested at CERN using the same electronics as for the GRPCs. In addition to these two developments, another technology using GEM detector is ongoing. As for the Micromegas a 1m^2 detector made of six assembled GEM is envisaged with 1cm^2 segmentation. Tests with one of those six GEM (33×50cm^2) were successfully achieved using binary readout electronics. Another important activity of the CALICE collaboration that has started recently is the one which intends to test the different HCAL technologies using a mechanical structure with tungsten as the absorber. This activity will be of the utmost interest for finding the best HCAL for the CLIC project.

4.3 Readout electronics and acquisition system

Different ASICs were developed within the CALICE collaboration for both the physics and the technological prototypes. The new generation of electronics is tiny, multi-channel and detector-embedded to cope with the linear collider experiment requirements. Some of the new ASICs address the power consumption problem by a power-pulsing scheme in which the electronics are powered only during data taking. Taking into account the ILC duty cycle of 5Hz with a bunch crossing duration of about 1ms, applying this scheme provides a factor of 100 reduction in power.



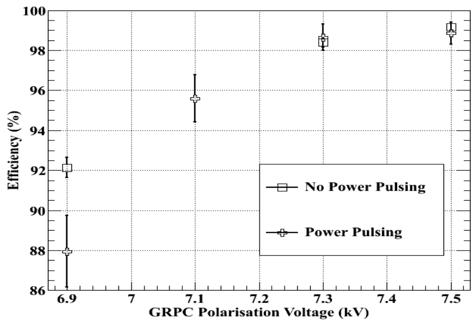


Figure 5: GRPC equipped with power-pulsed electronics in the H2 3-Tesla magnet at SPS-CERN (left) and comparison between efficiency with and without power pulsing scheme in the same field.

This power pulsing scheme was recently tested with the HARDROC ASICs associated to a 50×33cm^2 GRPC in a magnetic field of 3 Teslas at CERN and found to be operational. No loss of efficiency was observed when the electronics was switched at least 1ms before the beam arrival as shown in figure 5. In addition to the readout electronics, important efforts were made to develop a new acquisition system allowing to address a huge number of ASICs. The system that is common to all the CALICE technological prototypes allows the loading of the configurations associated to each ASIC. It organizes the data transmission from the ASICs. It provides also a common clock necessary to sort out the collected data. The system will be used for the first time in the SDHCAL prototype.

5. Conclusion

The CALICE collaboration has conceived and built highly-granular electromagnetic and hadronic calorimeter prototypes with different technologies. The results obtained with the first prototypes confirm the possibility of applying the PFA concept using these calorimeters. They provide also a better understanding of hadronic shower behavior. The CALICE collaboration is developing also a new generation of prototypes taking into consideration the problems related to integration in the future linear collider experiments. The first prototypes are foreseen to be operational in 2011.

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