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CALICE[1] Prototype Calorimeters for Linear Collider Detectors

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For several years, CALICE has been testing highly granular calorimeter prototypes using analogue readout. These devices are envisaged for particle flow [1] application in a future linear collider detector. A novel alternative, especially interesting for the hadron calorimeter, is to use a simplified digital (= 1 – bit) readout coupled with very small cell sizes. In the past year the first large scale ($1m^3$) digital HCAL has been operated by CALICE in test beams at Fermilab. This detector uses glass RPCs as active elements within an iron absorber structure. The RPCs are read out through 1x1 cm^2 pads with a single threshold, providing a digital image of the hadronic or electromagnetic shower with high spatial resolution. We report on the technical performance of this calorimeter, and show first physics results on shower reconstruction.

A related approach is to use RPCs with two-bit readout, providing three threshold values, referred to as a "semi-digital" HCAL. In 2010 a full $1m^2$ plane was tested in a beam, and a full $1m^3$ is being tested at CERN in 2011. The electronics of the prototype was "power pulsed", a technique which is envisaged to reduce power dissipation in an ILC detector [3]. The performance of these RPCs was also tested in a 3T magnetic field. Alternative technologies for a digital HCAL are also being studied, both Micromegas, for which $1m^2$ planes have already been tested in beams, and GEMs for which 30x30 cm^2 units are currently being tested.

Second generation analogue devices are also under construction, and we report progress here. The focus of this work is to develop technical solutions which could be scaled up to a full-size detector. We report the development of a highly segmented electromagnetic calorimeter based on silicon sensors with 5x5 mm^2 segmentation, covering details of the sensor design, readout electronics and the mechanical and thermal issues of detector integration. An alternative technology based on scintillator-strip sensors is also being developed. The second generation analogue HCAL is based on scintillating tiles that are individually read out by silicon photomultipliers. The prototype will contain about 2500 detector channels, corresponding to one calorimeter layer.

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1.Introduction

A future lepton collider will address exciting new physics and perform precision measurements. In order to achieve unprecedented jet energy resolution, the detector system at a future lepton collider will be optimized for the application of Particle Flow Algorithms (PFA's) [1]. PFAs measure the charged particles in a jet using the tracking system and only measure the photons and neutral hadrons with the calorimeter system. The role of calorimetry, in this case, has evolved to measure the energy of only the neutral particles and to provide clear separation between signals from charged particles and from neutral particles. In order to achieve this goal, optimization for the application of PFAs needs very finely granular calorimeters, which are also often called imaging calorimeters.

In this context, the CALICE collaboration (CAlorimeter for LInear Collider Experiment) [4] has developed and tested a 1st generation of prototypes, often called the physics prototypes, for a number of imaging calorimeter technologies, first with analog readouts, then with novel digital readouts. The collaboration is currently developing the 2nd generation prototypes, often called the technical prototypes, which are designed to solve all the technical issues in building a real calorimeter system for a future colliding beam experiment. We report on the CALICE 1st generation prototypes with digital readout and on the status of the 2nd generation prototypes.

2.CALICE Prototypes with Digital Readout

For several years, CALICE tested 1st generation imaging calorimeter prototypes using analogue readout. A novel alternative, especially interesting for the hadron calorimeter, is to use digital readout with a very small cell size. A calorimeter with digital readout only records hit patterns according to 1 or more discreet thresholds, instead of the pulse height information in each individual cell, as in a calorimeter with analog readout. This approach significantly simplifies the complexity and cost of the readout system for an imaging calorimeter and makes small cell sizes practical for a hadron calorimeter. The CALICE collaboration developed a Digital Hadron Calorimeter (DHCAL) prototype which is based on glass RPC's and uses 1-threshold readout. A similar device, the semi-Digital Hadron Calorimeter (sDHCAL) prototype, which also uses glass RPC's and has a 3-threshold readout, is also being developed.

2.1 RPC DHCAL

The CALICE RPC DHCAL group adopted the digital readout concept and chose Resistive Plate Chambers (RPCs) as the active medium, since these are a perfect match for the digital calorimeter concept. The RPC's are highly efficient in detecting charged particles, good in terms of position resolution (no problem with small readout cells), very thin, very reliable, and not expensive to build. The signal charge of RPCs is not well correlated with the energy lost by particles in the gas gap, but that is NOT needed for a digital calorimeter. The group developed a thin RPC design and a digital readout system built around a front end ASIC (the DCAL chip [5]) that was developed specifically for the DHCAL. The design was tested successfully with a small (~2.5k channels) prototype. Based on the success of the small prototype, a large $1m^3$

prototype was build with 38 active layers between 2008 and 2010. Figure 1 shows the complete $1m^3$ stack before cabling up and a 32 GeV pion shower measured in it. Each layer is $1m^2$ in size, and consists of 3 glass RPC's, 32x96 cm^2 each, and is readout by 6 front end boards with 1x1 cm^2 size readout pads. Each layer has 9,216 channels, and the total thickness of the active elements, including the readout, is 8.6 mm. Later on, 14 more identical active layers were built to equip a tail catcher, which brings the total channel count to ~500k. This constitutes the largest number of channels for any calorimeter that was ever built.

The prototype went through several rounds of tests in the test beam at Fermilab using steel plates as absorber. The group foresees one more round of beam tests with low energy beams (0.2 – 2 GeV) at Fermilab in the fall of 2011. In 2012 the RPCs will be tested at CERN with tungsten absorber plates.

Even though the $1m^3$ prototype is often called the physics prototype, it has some features that are standard on many of the CALICE 2^{nd} generation prototypes. This is the first large scale prototype with embedded front-end electronics, and a hardware data aggregation structure that is very similar to 2^{nd} generation CALICE DAQ system. The group also started R&D efforts to address other remaining issue in building a technical prototype.

2.2 RPC sDHCAL

The CALICE RPC sDHCAL effort also chose RPCs as the active medium but has a different approach to the readout. The sDHCAL group utilizes three thresholds in their readout, unlike the single threshold in the digital readout case, and uses the additional information to improve the linearity and energy resolution from a pure digital calorimeter. The group finished building a large ~$1m^3$ prototype in summer 2011. The prototype consists of 47 active layers that are inserted into a very compact steel absorber structure. Figure 1 shows the finished $1m^3$ stack and a muon track measured in it. Each detector plane is about $1m^2$, consists of 1 glass RPC, and is readout by 6 front end boards with 1x1 cm^2 signal pads. The readout system is built around a front-end ASIC (the HARDROC chip [6]) and has the same channel counts per plane as the RPC DHCAL. The sDHCAL prototype had three test beam periods at CERN in 2011, and foresees more tests in particle beams in 2012.

The $1m^3$ sDHCAL prototype addresses many issues of a technical prototype, including fully embedded front-end electronics, an integrated compact mechanical structure, thin active layers (only ~6 mm for the active elements, including readout), daisy chained front end boards, and power-pulsed front-end chips.

Figure 1: from left to right, DHCAL physics prototype stack before cabling; 32 GeV pion shower measured in DHCAL; sDHCAL physics prototype stack; muon track measured in sDHCAL.

2.3 Other DHCAL developments

CALICE is also developing DHCAL technologies using micromegas and GEM detectors as the active medium. Both the micromegas and GEM chambers have excellent position resolution and can operate efficiently in high rate environments. The micromegas group developed embedded readout with a front-end ASIC (the MICROROC chip [6]) that was optimized for the readout of micromegas. A few detector planes of size $1m^2$ have been successfully built and tested in particle beams. These detector planes have been inserted into the sDHCAL prototype stack and will be tested together with the sDHCAL prototype. The GEM group has built several GEM chambers of size 30x30 cm^2, and tested these chambers with both the KPiX chip [7] and the DCAL chip using cosmic rays. The GEM group also tested these chambers in the Fermilab test beam in summer 2011. The group plans to build several detector layers of size 1 m^2 and test them in particle beams.

3. CALICE technical prototypes

The CALICE technical prototypes are meant to be prototypes of a real calorimeter system, including technical solutions to all practical issues, like services and cooling. With the success of the physics prototypes using analog readout, the CALICE Si-W ECal group, Scintillator-W ECal group and the Scintillator analog HCal (AHCAL) group are the first groups to move forward on developing technical prototypes.

3.1 Si-W and Scintillator-W ECal

The CALICE Si-W ECal group uses thin silicon wafers that have been segmented into a square pad matrix as the active medium, where each square on the wafer is a calorimeter cell. When combined with tungsten absorber plates, the electromagnetic calorimeter is very dense and has a small Moliere radius, with the effect to confine EM showers radially. The Si-W group has built a physics prototype that consisted of 30 silicon layers. The cell size for the physics prototype was chosen to be 1x1 cm^2. The readout system of the physics prototype sits outside the detector stack. The physics prototype was tested successfully with particle beams [8].

The group is currently developing a technical prototype that has several major changes from the physics prototype, including smaller readout cell sizes (5x5 mm^2) on larger wafers, an embedded readout system built around the SKIROC ASIC [6] with power pulsed front-end, an integrated mechanical structure, and realistic service and cooling. The active layer is optimized for minimum thickness by using a very thin PCB and wire bounded front end chips without bulky packaging. The prototyping and testing of individual components is ongoing, and the first beam tests are expected in 2012/2013. The group also tested their embedded readout ASIC at the shower maximum of 70 – 90 GeV electromagnetic showers, and found no sizable effect on the measured noise spectrum, compared to the no-beam condition[2].

The CALICE Scintillator-W ECal effort uses scintillator strips as the active medium and readout by MPPC's [9]. The strips are 4.5 cm long and 1 cm wide, and they are placed in orthogonal directions in alternating layers. This group produced a physics prototype that has an active area of 18x18 cm^2 in each layer and is 30 layers deep. This prototype was tested extensively in particle beams and the data analysis is almost completed. The group is proceeding with R&D towards a technical prototype, collaborating with other CALICE groups on the mechanical structure and embedded readout.

3.2 Scintillator analog HCal (AHCAL)

The CALICE scintillator AHCAL effort uses small scintillator tiles of the size 3x3 cm^2 and read out by SiPM's as the basic cells of their calorimeter. The group built a large physics prototype of the size of about $1m^3$, which consists of 38 detector planes. The physics prototype was tested extensively with particle beams using both steel absorber plates [10] and tungsten absorber plates.

The group is currently developing a technical prototype, which will have a wedge shape, an embedded readout system built around a front-end ASIC (the SPIROC2 chip [6]), and an embedded calibration system. The basic unit of the active layer consists of a front-end board that hosts 4 ASICs, reads out 144 scintillator tiles with individual SiPMs and hosts an LED calibration system. The new version of the SPIROC ASIC reads out 36 channels, has an additional auto trigger running mode, provides nano-second level timing, and is able to power-pulse the front-end. The scintillator tiles are attached to the back of the front-end board and are aligned with 'LEGO' like alignment pins. The calibration system, which provide gain and saturation calibration for the SiPMs, has the LEDs mounted on the front-end board that couples directly to the scintillator tiles.

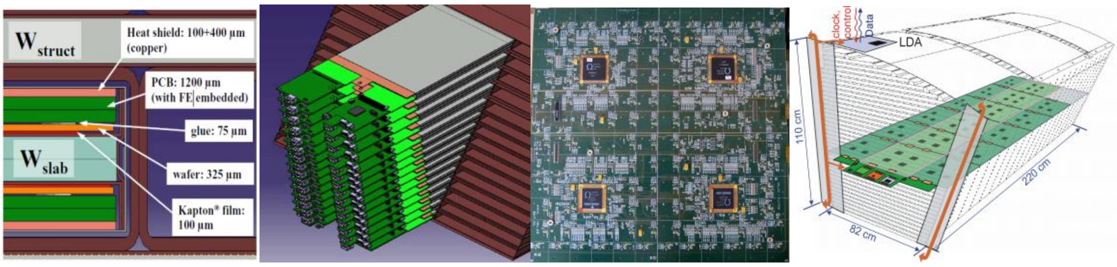

Figure 2: from left to right, Si-W ECal technical prototype active layer structure and stack configuration; AHCAL technical prototype front-end board and wedge configuration.

4. Summary

Imaging calorimeters will be key ingredients of a detector system at a future lepton collider. The CALICE collaboration developed 1st generation (physics) prototypes to proof that fine grained calorimeters can be built and deliver the expected physics performance. The collaboration is developing 2nd generation (technical) prototypes to demonstrate that imaging calorimeters can be built for a detector system at a colliding beam experiment.

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