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Construction and Testing of the CALICE Digital Hadron Calorimeter

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The large CALICE Digital Hadron Calorimeter prototype (DHCAL) was built in 2009 - 2010 and was tested in the Fermilab and CERN test beams. The DHCAL uses Resistive Plate Chambers (RPCs) as active media and is read out with 1 x 1 cm^2 pads and digital (1 - bit) resolution. With a world record of nearly 500k readout channels, the DHCAL offers the possibility of studying hadronic interactions with unprecedented spatial resolution. Here we describe the construction process of the DHCAL and briefly report on the test beam program.

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1. Introduction

Detectors optimized for the application of Particle Flow Algorithms (PFAs) have been proposed to enable precision measurements at a future lepton collider. PFAs measure all particles (originating from the interaction point of a typical colliding beam detector) in a jet individually, using the detector component that provides the best momentum/energy resolution. The momenta of charged particles are measured with the tracking system (except for high momenta where the calorimeter provides a better measurement), the energy of photons are measured with the electromagnetic calorimeter (ECAL), and the energy of neutral hadrons, i.e. neutrons and K_L^0's, are measured with both the ECAL and the hadronic calorimeter (HCAL). The energy of a jet is reconstructed by adding up the energy of the individual particles identified as belonging to this jet. The major challenge in this approach lies in the identification of energy deposits in the calorimeter belonging to either a charged or neutral particle, hence the requirement of calorimeters with very fine segmentation of the readout. Additional details on PFAs and the requirements for calorimetry can be found in [1].

For a future lepton collider detector, the key emphasis is on the identification and measurement of the W, Z and Higgs bosons and of heavy quarks and leptons. This wide spectrum of measurement-ready physics could also get extended "by several orders" depending on the results of the LHC (discovery of new physics like SUSY, extra dimensions, etc.). In the event of this particle/phase-space extension, the challenge for the detectors increases even further. The solution requires increased segmentation in calorimeters. This high segmentation requirement can currently be achieved with a simple digital readout.

A digital calorimeter with Resistive Plate Chambers (RPCs) provides the necessary transverse segmentation, robustness, detection efficiency, readout integrity and radiation hardness demanded by a lepton collider. Apart from the readout concept, a digital calorimeter with RPCs offers negligible noise and background interference and well-identified environmental dependence. A high granularity calorimeter system (both electromagnetic and hadron calorimeters) with an efficient tracker will be the future of particle detectors. Current technically feasible solution for this kind of a detector approach is a calorimeter system with digital readout.

In this context, a so-called Digital Hadron Calorimeter (DHCAL) using RPCs as active elements and 1 cm x 1 cm readout pads with a single-bit readout has been developed. Here we report on the design, construction, quality control, and testing of the DHCAL.

2. Brief description of the DHCAL

The design of the DHCAL was based on the preliminary work done with a small scale prototype, which underwent a rigorous test program in the Fermilab test beam and resulted in numerous publications [2, 3, 4, 5, 6].

The DHCAL prototype in the Fermilab test beam consists of two parts: 1) a 38-layer structure with 17.5 mm thick steel absorber plates and 2) a 14-layer structure with eight 2.54 cm thick steel plates followed by six 10.0 cm thick steel plates. The former (latter) is commonly referred to as the Main Stack (Tail Catcher and Muon Tracker (TCMT)). These absorber structures were equipped with RPCs as active elements. Each layer measured approximately 1 x 1 m^2 and was inserted between neighboring steel absorber plates. The distance from layer-to-layer in the 38-layer structure was 3.17 cm.

In addition to this standard configuration, the data was also collected with 50 layers in a structure without additional absorber plates. In this configuration, the skins of the detector cassettes (2 mm Copper and 2 mm Steel) and the glass of the RPCs served as the only absorber material. Here the layers were spaced 2.54 cm apart.

In the CERN test beam, the DHCAL consisted of 54 active layers. 39 of these layers were inserted into the CERN Tungsten absorber structure featuring 1 cm thick Tungsten plates (Main Stack), and 15 of them were placed in the TCMT where the first 8 layers had 2 cm and the remaining layers had 10 cm steel absorbers. The distance between the plates in the Main Stack was 15 mm, of which 12.85 mm were filled by the cassette structure of the active layers. More information about the Fermilab and CERN test beams can be found in [7].

Each DHCAL active layer consists of three RPCs, each with an area of 32 x 96 cm^2 and stacked vertically on top of each other to create a 1 x 1 m^2 active area. Each RPC in turn is read out with two readout boards, which covered the entire gas volume of the chambers. The three chambers and their boards are contained in a cassette structure providing the mechanical protection during transportation and installation.

Each RPC is read out by 3072 1 x 1 cm^2 pads located on the bottom side of the readout boards. To first order, the charges generated by single avalanches in RPCs are determined by the ionization in the gas gap furthest away from the anode, and thus subject to the largest multiplication. This leads to a wide range of signal charges [8] which are if at all only weakly correlated to the energy loss in the gas gap. Therefore, a precise measurement of the induced charge is only of limited interest. As a consequence, the DHCAL readout is simplified to a single threshold per pad, hence digital readout.

The DHCAL has the following unique features: RPCs for calorimetry (no other hadron calorimeter uses RPCs as active medium), pad readout of RPCs (RPCs are usually read out with strips), digital readout, embedded front-end electronics and large channel count (a world record of 0.5M channels).

3. RPC Design

The DHCAL RPC design consists of two glass plates separated by 1.15 mm. Figure 1 shows the schematic of the RPC. The thickness of the anode (cathode) glass plates are 0.85 (1.15) mm. The thinner glass on the anode side is to keep the average number of pads with signals above threshold as close as possible to unity for minimum ionizing particles crossing the gas gap. They are glued to a plastic frame and are held apart by fishing lines placed 5 cm apart. The latter also provide a path for the gas to flow uniformly through all parts of the chamber. A unique 1-glass RPC has also been developed at Argonne, but was not used for the assembly of the DHCAL. The total RPC thickness is approximately 3.4 mm and has a dead area of 5% including the frame and fishing lines.

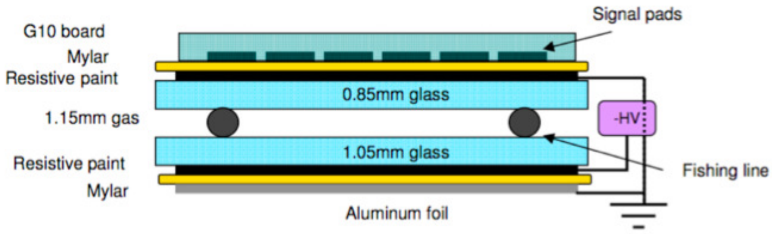


Figure 1: Schematic of the DHCAL RPC (not to scale).

4. RPC Assembly and Quality Control

To apply a high voltage on the outside of the chamber, a paint with a uniform surface resistivity of 1 to 5 MΩ/□ needs to be applied. The lower bound on the value is defined by the requirement to keep the average pad multiplicity for minimum ionizing particles as close to unity as possible. The upper bound is to avoid efficiency losses at higher particle fluxes. Values on the thicker plate are less stringent.

The required surface resistivity was obtained with a two component 'artist' paint. This non-toxic paint was applied with a spray gun mounted on a computer controlled arm. The application took approximately 2 minutes/plane, apart from a significant set-up and cleaning time. After the paint had dried, the surface resistivity was measured in a grid over the entire surface of the glass. The uniformity over the surface was in general adequate.

Chamber assembly was accomplished in the following sequence: The plastic frame was cut to size and glued together on a custom gluing fixture to provide the correct shape and outer structure. Next, a sheet of thick painted glass was placed on the frame and glued to achieve rigidity and create a seal to contain the gas. After allowing the glue to dry overnight, the frame and glass were flipped over. Four nylon fishing lines, covered with plastic sleeves (1.15 mm diameter) to approximately 90% of their lengths were inserted with tension across the length of the glass. The sleeves were positioned so as to form a path to direct the gas flow from the input to the output. Next, a sheet of thin painted glass was placed over the frame and glued in place. Once the glue was dry, the gas inlet tubes, high voltage mounting fixtures and the fishing lines were glued in place. Finally, the RPCs were covered with insulating mylar, and the high voltage cables were attached. Figure 2 shows a photograph of an assembly station including a partially completed chamber with fishing lines/gas spaces installed.

Once assembled, the chambers go through the following quality control checks:

- Pressure tests to test whether the chambers are sealed
- Gap size measurement to maintain uniform electric field in gas gap
- High voltage tests
- Cosmic Ray Test Stand (9 RPCs stacked vertically) in order to validate production, test front-end electronics, perform noise measurements and high volage scans to test efficiency and multiplicity.

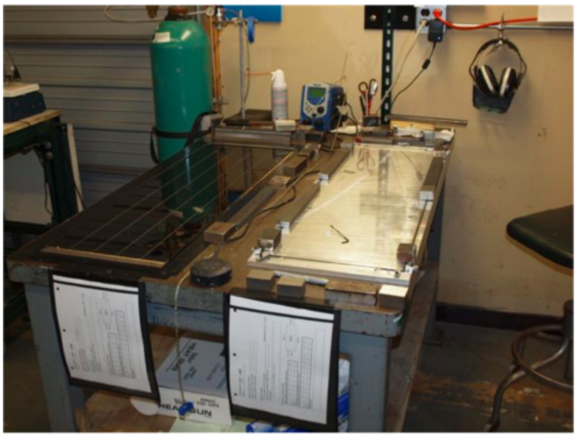


Figure 2: Picture of the RPC assembly station.

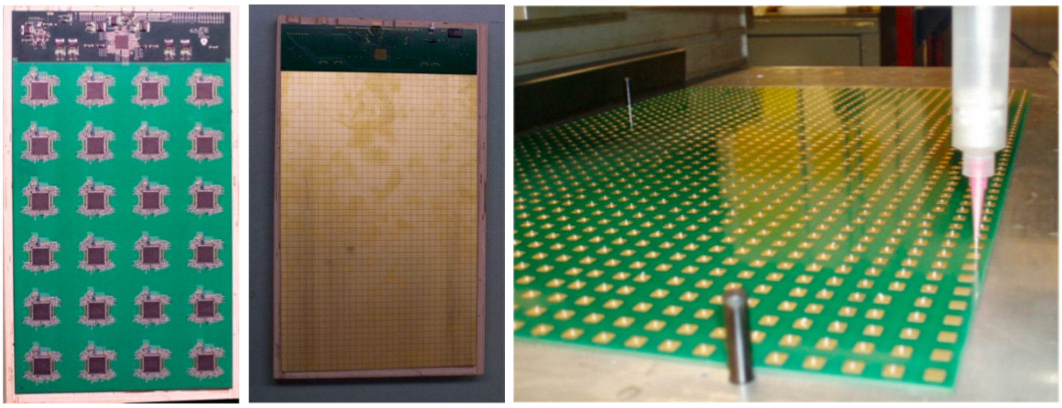
More than 95% of all the RPCs passed the quality control tests.

5. Readout Electronics

The readout of the chambers was performed with a 64-channel ASIC, the DCAL chip developed jointly by Fermilab and Argonne. It operates in two gain modes: a high gain appropriate for use with GEMs and micromegas with a minimum threshold of approximately 5 fC and a low gain appropriate for use with RPCs with minimum threshold of approximately 30 fC. Each DCAL chip has a threshold that is set by an 8-bit DAC (up to around 600 fC) that is common to all 64 channels. In addition to a triggered readout mode for cosmic rays and test beam data collection, a triggerless mode is available for noise measurements.

Each RPC was read out by 32 x 96 pads or a total of 3072 pads or channels. Two circuit boards covered the active surface of a chamber, each having 1536 pads and requiring 24 DCAL chips. A data concentrator is implemented into the same board. The front end (FE) board and pad board were manufactured separately to avoid blind and buried vias, a cost and feasibility issue. The pads on the pad board were connected to so-called gluing pads on the other side of the board. These in turn were connected to gluing pads on the front-end board using conductive epoxy. Figure 3 shows the front-end board (a), pad board (b) and the gluing machine putting the glue on the gluing pads. The assembled readout boards were dried in the oven overnight. The production rate was around 10 boards per day.

The readout operation overlaps signal acquisition, making noise performance critical. The data is read out serially from the front-end boards using "data push" into custom VME cards in the back-end system called Data Collectors. The data are time-sorted using the timestamps, and are stored in readout buffers. The data are read periodically into a computer, where higher-level algorithms perform the event reconstruction. In addition, the Data Collectors provide an interface to the front-ends for slow control communication and timing. The VME crate that hosts the Data Collector also contains a Timing and Trigger Module that receives timing and trigger signals from



(a) (b) (c)

Figure 3: Picture of a front-end board (a), pad board (b) and the gluing machine that puts the conductive epoxy at the gluing pads which are on the reverse sides of the front-end and pad boards.

peripheral subsystems and communicates with the Data Collectors to provide this information to the front-ends.

6. Cassette Assembly

Once the assmebly of the RPCs and the readout boards are completed, the detector cassette is constructed with a 2 mm steel back, three RPCs, six front-end board/pad board combinations and a 2 mm copper front piece. The cassette is compressed horizontally with a set of 4 (Badminton) strings. The strings are tensioned to around 20 lbs each. This keeps the copper plate in thermal contact with the surface of the DCAL chips for cooling purposes. Each cassette took approximately 45 minutes to assemble. The cassettes were tested with cosmic rays before being shipped to the test beams. Figure 4 shows the partially equipped and cabled test beam stack.

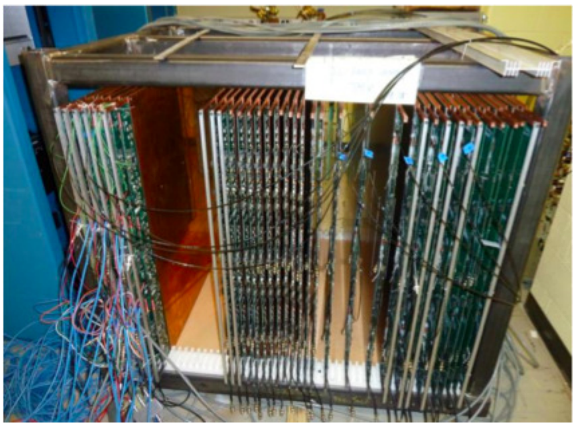


Figure 4: Partially equipped and cabled test beam stack. In this campaign, the DHCAL was tested with no absorber material in between the cassettes.

7. The DHCAL in the Test Beams

The DHCAL was tested in the Fermilab test beam using 120 GeV primary proton beam, the secondary beams with a wide range of energies and the broadband muon beam. Part of this test beam program included combined tests with the CALICE SiW Electromagnetic Calorimeter and tests with minimal absorbers where a stack of cassettes were exposed to the beam with no arsorber plates in between (see Fig. 4). The Fermilab test beam data consists of approximately 30M events.

The DHCAL was also tested in the CERN test beam with Tungsten absorber plates in 2012. The data consists of more than 40M events of secondary beam particles with energies ranging from 1 to 300 GeV.

8. Summary

We have built and tested the world's first large-scale Digital Hadron Calorimeter (DHCAL) prototype. The DHCAL utilizes Resistive Plate Chambers (RPCs) as active elements. The readout is segmented into 1 x 1 cm^2 pads that are individually read out with 1-bit resolution (=1 threshold = digital readout). Due to its fine segmentation and large size, the prototype holds the world record in channel counts (approximately 500,000) both for calorimetry and for RPC systems.

The prototype was extensively tested with Cosmic Rays, and in the Fermilab and CERN test beams. It performed according to expectations. The DHCAL constitutes the first large scale imaging hadron calorimeter suitable with the application of Particle Flow Algorithms (PFAs). The test beams resulted in the observation of hadronic showers with unprecedented spatial resolution and in the validation of the DHCAL concept.

References

[1] M.A. Thomson. Particle flow calorimetry and the pandorapfa algorithm. *Nucl.Instrum.Meth. A*, 611(1):25 – 40, 2009.

[2] B. Bilki et al. Calibration of a digital hadron calorimeter with muons. *Journal of Instrumentation*, 3(05):P05001, 2008.

[3] B. Bilki et al. Hadron showers in a digital hadron calorimeter. *JINST*, 4(10):P10008, 2009.

[4] B. Bilki et al. Measurement of positron showers with a digital hadron calorimeter. *JINST*, 4(04):P04006, 2009.

[5] B. Bilki et al. Measurement of the rate capability of resistive plate chambers. *JINST*, 4(06):P06003, 2009.

[6] Q. Zhang et al. Environmental dependence of the performance of resistive plate chambers. *JINST*, 5(02):P02007, 2010.

[7] J. Repond. First results from the calice digital hadron calorimeter (dhcal). *Talk given at this conference*.

[8] G. Drake et al. Resistive plate chambers for hadron calorimetry: Tests with analog readout. *Nucl.Instrum.Meth. A*, 578(1):88 – 97, 2007.