Snowmass2021 - Letter of Interest

[Digital Hadron Calorimetry]

Instrumentation Frontier Topical Groups: (check all that apply □/■)

□ (IF1) Quantum Sensors
□ (IF2) Photon Detectors
□ (IF3) Solid State Detectors and Tracking
□ (IF4) Trigger and DAQ
□ (IF5) Micro Pattern Gas Detectors (MPGDs)
■ (IF6) Calorimetry
□ (IF7) Electronics/ASICs
□ (IF8) Noble Elements
□ (IF9) Cross Cutting and Systems Integration

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Collaboration (optional):

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Abstract: The Particle Flow Algorithms attempt to measure each particle in a hadronic jet individually, using the detector providing the best energy/momentum resolution. Therefore, the spatial segmentation of the calorimeter plays a crucial role. In this context, the CALICE Collaboration developed the Digital Hadron Calorimeter.

The Digital Hadron Calorimeter uses Resistive Plate Chambers as active media and has a 1-bit resolution (digital) readout of 1 x 1 cm^2 pads. The calorimeter was tested with steel and tungsten absorber structures, as well as with no absorber structure, at the Fermilab and CERN test beam facilities over several years. In addition to conventional calorimetric measurements, the Digital Hadron Calorimeter offers detailed measurements of event shapes, rigorous tests of simulation models and various tools for improved performance due to its very high spatial granularity.

This Letter of Interest describes the development of the Digital Hadron Calorimeter with various measurements and indicates the future implementations in which the Digital Hadron Calorimeter has a high potential to fully exploit the benefits of the Particle Flow Algorithms.

The High Energy Physics community has come to a consensus that the achievement of the high precision measurements aimed in future experiments, such as the ones envisaged at the International Linear Collider (ILC) [1], Compact Linear Collider (CLIC) [2] and Future Circular Collider (FCC) [3], can be made possible with the utilization of the Particle Flow Algorithms (PFAs) [4]. A detector optimized for the implementation of PFAs requires calorimeters with extremely fine segmentation of the readout to separate showers from charged and neutral particles. In this context, the CALICE collaboration [5] developed several high segmentation calorimeters.

The large Digital Hadron Calorimeter (DHCAL) prototype was built in 2008-2010, following the successful completion of the test beam program of a small size prototype. The latter produced a number of interesting results [6] and served as basis for the design of the DHCAL.

The DHCAL uses Resistive Plate Chambers (RPCs) as active media and is read out with 1 x 1 cm^2 pads and 1-bit resolution (digital). A single layer of the DHCAL measures roughly 1 x 1 m^2 and consists of 96 x 96 pads. The active layers were placed between different absorber structures, to be described in detail below. In addition to the absorber plates, each layer of RPCs was contained in a cassette with a 2 mm thick Copper front plate and a 2 mm thick Steel back plate. The details of the DHCAL are given in [7].

In order to obtain a unique dataset of electromagnetic and hadronic interactions with unprecedented spatial resolution, the DHCAL went through a broad test beam program. The DHCAL was tested with steel and tungsten absorber structures, as well as with no absorber structure, at Fermilab and CERN test beam facilities over several years. In addition to conventional calorimetric measurements, the DHCAL offers detailed measurements of event shapes, rigorous tests of simulation models and various tools for improved performance due to its very high spatial granularity.

During the tests at Fermilab Test Beam Facility (FTBF) [8], up to 52 layers were installed. The calorimeter consisted of a 38-layer main stack with 1.75 cm thick steel absorber plates and a 14-layer tail catcher with eight 2 cm thick steel plates followed by six 10 cm thick steel plates. This test setup is called the “Fe-DHCAL”.

The “W-DHCAL” consisted of 54 active layers interleaved with Tungsten absorber plates [9]. The first 39 of these layers were inserted into the CERN tungsten absorber structure [10], featuring 1 cm thick tungsten plates and in the following named the main stack. The distance between the plates was 15 mm, of which 12.85 mm were occupied by the cassette structure of the active layers. The remaining 15 layers were inserted into a steel structure, the tail catcher, which was located 23.5 cm behind the main stack. The total thickness of the 54-layer W-DHCAL (main stack and tail catcher) corresponded to approximately 183 radiation lengths or 11.1 nuclear interaction lengths.

In special tests, 50 active layers of the DHCAL were exposed to low energy particle beams, without being interleaved by absorber plates. The thickness of each layer corresponded approximately to 0.29 radiation lengths or 0.034 nuclear interaction lengths. This minimal absorber material configuration is called the “Min-DHCAL” [11]. The Min-DHCAL was exposed to the test beam at FTBF. Runs were taken with a selected momentum in the range of 1 - 10 GeV/c. The simulation of the test beam set-up is based on the GEANT4 version 10.02 with default parameters and FTFP_BERT_EMY physics list [12]. Any energy deposition generated by the simulation in the gas gap of the RPCs is used as a seed for creating an avalanche. The response of the RPCs is simulated using a standalone program, called RPC_sim [6].

The DHCAL data contain the hit position information, the time stamp of the individual hits and the time stamp from the trigger and timing unit. Additionally, discriminated signals from a beam Cerenkov counter and a muon tagger (the downstream scintillator 1 x 1 m^2 paddle) are integrated into the data stream by the data acquisition system.

The stochastic term of the Fe-DHCAL resolution for pions is 66 % (64 %) and the constant term is 4 % (3 %) for the uncalibrated (density-weighted calibration) data. The W-DHCAL with 1 x 1 cm^2 readout pads is strongly overcompensating, even at low energies which is in contrast to what was observed with Fe-DHCAL, where the response is compensating in the range of 8 - 10 GeV/c and under- (over-) compensating below (above). The W-DHCAL hadron (electron) response shows the characteristic behavior of calorimeters with 68.0 % (29.4 %) stochastic term and 5.4 % (16.6 %) constant term.

The high spatial segmentation of the imaging calorimeters allow the application of corrections to the measured number of hits which might result in an improved linearity of the response and energy resolution [13]. The DHCAL data can be corrected for leakage using the detailed shower profiles, and the response can be linearized by assigning different weights to hits based on their densities. For example, the density-weighted linearization procedure for the Min-DHCAL data results in a modest improvement of about 10 %. The stochastic terms obtained before and after the linearization procedure are 14.8 ± 0.4 and 13.0 ± 0.4 respectively.

In summary, the first Digital Hadron Calorimeter was built and tested successfully, and the concept of Digital Hadron Calorimetry is validated. By construction, the DHCAL was the first large-scale calorimeter prototype with embedded front-end electronics, digital readout, pad readout of Resistive Plate Chambers and extremely fine segmentation.

Fine segmentation allows the study of electromagnetic and hadronic interactions with unprecedented level of spatial detail, and the utilization of various techniques not implemented in the community so far e.g. software compensation and leakage correction.

Standard Geant4 simulation package fails to reproduce data well. Some optional packages allow big improvement in the agreement. The disagreements are at the very fine level of detail which is not available in conventional calorimeters.

The Digital Hadron Calorimeter is a unique solution to calorimetry implementations where cost effectiveness, fine segmentation, large-scale and robustness are optimized in an unprecedented manner.

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