Status of the CALICE Digital Hadron Calorimeter

Burak Bilki
On behalf of the CALICE Collaboration

***Abstract*—A novel approach named Particle Flow Algorithms is proposed to measure the jets of the hadronic decays of electroweak bosons in a future lepton collider with 3-4% resolution. The Particle Flow Algorithms attempt to measure each particle in a hadronic jet individually, using the detector subsystem providing the best energy/momentum resolution. In this paradigm, the role of the hadronic calorimeter is to measure the neutral hadron component of the hadronic jets. In this context, the CALICE Collaboration developed the Digital Hadron Calorimeter, which uses Resistive Plate Chambers as active media. The 1-bit resolution (digital) readout of 1 x 1 cm^2 pads achieves a world record in the number of readout channels already at the prototyping stage. Here we report on the status of the Digital Hadron Calorimeter with results from several Fermilab test beam campaigns with an emphasis on the intricate calibration procedures.**

I. Introduction

At a future lepton collider, such as the ILC or CLIC, the measurement of hadronic jets will play an important role in discovering or exploring physics beyond the current Standard Model of Particle Physics. Indeed, both the energy resolution and the mass resolution of multi-jet systems will be important in defining the physics reach of this new facility. Of particular interest will be the identification of electroweak bosons through their hadronic decay. Identification on an event-by-event basis will require an energy resolution of the order of 3-4% for a wide range of jet energies.

A novel approach, named Particle Flow Algorithms (PFAs) is proposed to achieve this unprecedented jet energy resolution [1]. PFAs attempt to measure each particle in a hadronic jet individually, using the component providing the best energy/momentum resolution. In this approach, charged particles are measured with a high-precision tracker, photons with the electromagnetic calorimeter and the remaining neutral hadronic particles with the combined electromagnetic and hadronic calorimeters.

In this context the CALICE collaboration developed the Digital Hadron Calorimeter (DHCAL). The large 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 [2], [3], [4], [5], [6], [7] 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 digital (1 - bit) resolution. A single layer of the DHCAL measures roughly 1 x 1 m^2 and consists of 96 x 96 pads. During the Fermilab beam tests, up to 52 layers were installed. The calorimeter consisted of a 38-layer structure (main stack) with 1.75 cm thick steel absorber plates and a 14-layer structure (tail catcher) with eight 2 cm thick steel plates followed by six 10 cm thick steel plates. 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 [8], [9].

The DHCAL is a calorimeter with the following unique features:

- RPCs for calorimetry (no other hadron calorimeter uses RPCs as active medium),
- Pad readout of RPCs (RPCs are usually readout with strips),
- Digital readout,
- Embedded front-end electronics,
- Large channel count (a world record of 0.5M channels).

Here, we report on the response of the DHCAL to pions with an emphasis on the intricate calibration procedures and their implementation in the analysis of the Fermilab data.

II. Calibration of the DHCAL

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 Čerenkov counter and a muon tagger (a downstream scintillator 1 x 1 m^2 paddle) are integrated into the data stream.

First, the hits in each layer are combined into clusters using a nearest-neighbor algorithm. The cluster's x and y coordinates are calculated as the average of these coordinates over the constituent hits. A right-handed coordinate system with the origin at the center of the most upstream layer is chosen. The event selection requires at least five active layers (layers with at least one hit) in order to eliminate events with spurious triggers.

The calibration of the DHCAL involves several steps. To begin, the performance parameters of the individual RPCs, i.e. the efficiency to detect a minimum ionizing particle and the average pad multiplicity, are measured. Here two methods are used: track fits and track segment fits. Dead or hot cells, if any, are identified on a run-by-run basis. In order to avoid a bias in the estimation of the performance parameters, regions within 1 cm of dead/hot cells or RPC edges are excluded from these measurements.

In a second step, the number of hits measured in a given RPC is corrected for differences in its performance parameters.

Manuscript received November 30, 2014.
Burak Bilki is with University of Iowa, Iowa City, IA 52242 USA and Argonne National Laboratory, Argonne, IL 60439 USA (e-mail: burak-bilki@uiowa.edu).

978-1-4799-6097-2/14/$31.00 ©2014 IEEE

Three different approaches have been explored: full calibration, density-weighted calibration, and hybrid calibration.

The track fits method uses dedicated muon calibration runs to assess the performance parameters of individual RPCs. This method starts with grouping the clusters that are laterally within a distance of 3 cm of each other in different layers. At least one cluster in the first three and one cluster in the last three layers of the main stack are required. If the cluster size exceeds 4 hits in any two consecutive layers, the event is not used for calibration purposes. This selection is to exclude events with interactions within the DHCAL.

The group of clusters is then fit to the 3-dimensional parametric line $x = x_0 + a_x t$; $y = y_0 + a_y t$; $z = t$ excluding the clusters in the layer to be measured. $\Delta r/\Delta z$ of the track, where $\Delta r = \sqrt{\Delta x^2 + \Delta y^2}$, is required to be less than 0.5 pads/layer and the fit χ^2/ndf is required to be less than 1 cm (for simplicity, the errors on the cluster positions were taken as 1 cm). In the layer to be measured, clusters within 2 cm of the point predicted by the fit are searched for. If a cluster is found, the layer is counted as efficient, and inefficient otherwise. If the layer is efficient, the pad multiplicity is given by the size of the found cluster. If multiple clusters are found in this search, the pad multiplicity is given by the size of the cluster that is closest to the fit point.

The track segment fits method is developed to measure the calibration parameters using the track segments within hadronic showers. With this method, the DHCAL provides another unique feature in calorimetry: For operation in a colliding beam environment, the DHCAL does not need a dedicated calibration system, as track segments can be used to monitor the performance of the RPCs.

The method starts with searching for four clusters that are aligned within 3 cm in four different layers (pick layers). Each of these clusters is required to contain at most four hits, and to be isolated within a radius of 4 cm (no other clusters within 4 cm in the same layer). The track segment is then fit to the same parametric line defined above, $\Delta r/\Delta z$ of the track segment is required to be less than 0.5 pads/layer and the fit χ^2/ndf is required to be less than 1, as in the case of the track fits. This track segment is used to measure the performance parameters of a fifth layer (measurement layer). The measurement layer can either be within the layer span of the pick layers or outside, but only one measurement layer per track segment is allowed. In the measurement layer, clusters within 2 cm to the fitted track segment are searched for. If a cluster is found, the layer is measured as efficient, and inefficient otherwise. If the layer is efficient, the pad multiplicity is measured as the size of the found cluster.

Using these methods, the calibration factors per RPC per data taking run are obtained as $C_i = \varepsilon_i \mu_i / \varepsilon_0 \mu_0$ where ε_i and μ_i are the efficiency and the average pad multiplicity of RPC i and ε_0 and μ_0 are the average RPC efficiency and pad multiplicity of the entire stack, 0.96 and 1.56 respectively [9].

In the full calibration, the hits in RPC i are weighted by $1/C_i$.

The density-weighted calibration takes into account that pads collecting charge from several nearby avalanches, for instance in the core of a shower, require a different calibration procedure than pads measuring single tracks. In other words, a pad in the core of a shower will register a hit with minimal dependence on the performance characteristics of this particular RPC and it should be calibrated in a different way than a pad e.g. along a MIP track in the same RPC. In this approach, the calibration factors of a pad may, in general, depend on the local hit density (as a measure of the number of avalanches contributing to the signal charge of that pad), the energy of the incident particle, and the type of incident particle, in addition to the performance parameters of the RPCs. The number of avalanches contributing to the signal of a pad are assumed to be correlated with the local hit density. This density is calculated by counting the hits in a 3 x 3 array surrounding the hit. Hence the density of a hit can vary between 0 and 8. The density-weighted calbration provides the correction factors as a function of the hit density and the performance parameters.

The hybrid calibration utilizes the full calibration for the hits with 0 or 1 neighbors and the density-weighted calibration for the hits with higher densities.

Figure 1 shows the application of the three calibration schemes to the 4 GeV π^+ data. As expected, the uncalibrated data (black) show the largest amount of fluctuation in response between different runs. The full calibration (red), density-weighted calibration (green) and the hybrid calibration (blue) schemes all result in improved uniformity of the responses with significantly smaller fluctuations. All calibration schemes are successful in compensating for the slight differences in the RPC performance characteristics.

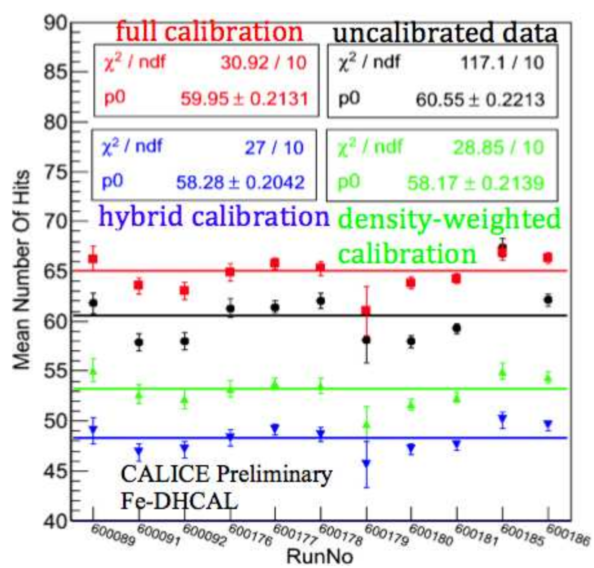

Fig. 1. The results of the three calibration schemes applied to the 4 GeV π^+ data. The uncalibrated data (black, 0), full calibration (red, 5), density-weighted calibration (green, -5) and the hybrid calibration (blue, -10) responses are all fit to a constant. The numbers in the parenthesis following the colors are the y-offsets applied to the data points in order to increase their visibilities. The error bars show the statistical errors on the means.

Figure 2 shows the χ^2/ndf for fits to a constant of the π^+ data collected in the Fermilab test beam. All calibration schemes improve the uniformity of the response across different runs and run periods. The three calibration schemes seem to perform at similar levels with no clear winner.

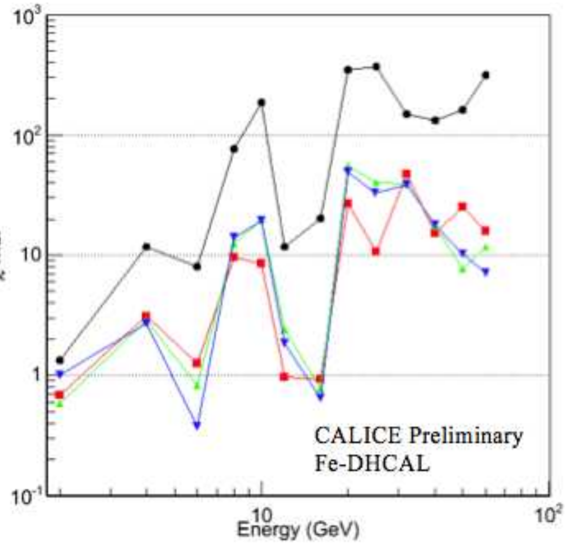

Fig. 2. Normalized χ^2 of the fits of a constant to all the π^+ data runs at a given energy.

The calibration procedures are described in detail in [10].

III. Response of the DHCAL to Pions

Figure 3 shows the mean response (a, c) and the energy resolution (b, d) for the uncorrected pion data (black), full calibration (red in a, b) and density-weighted calibration (green in c, d). The mean response is fit to the power function $N = aE^m$ up to and including 60 GeV. The resolutions are fit to the generic $\sigma(N)/N = \alpha/sqrt(E) \oplus C$ where α is the stochastic term and C is the constant term. The resolution fits are up to and including the 25 GeV point. The fitted curves are extrapolated to 60 GeV. No additional corrections/selections are applied to the data (e.g. containment cuts, correction for response non-linearity). Therefore, the purpose of Fig. 3 is to demonstrate the effect of the calibration schemes on the results.

All calibration schemes normalize the mean response to the predefined DHCAL operating conditions. At lower energies, the methods agree with each other. However, at higher energies where the shower densities are large, the effect of employing the density weighting in the calibration procedure is clearly visible.

IV. Recent Developments

A. *One-glass and Low-Resistivity Glass RPCs*

We designed and built novel one-glass RPCs and tested them with cosmic rays and at the Fermilab test beam. The advantages of the one-glass RPCs are close to unity pad multiplicity (which is a big advantage in terms of calibration), better position resolution in case smaller pads are desired, lower cost and higher rate capability. We built several large chambers and tested them with cosmic rays for several months without problems.

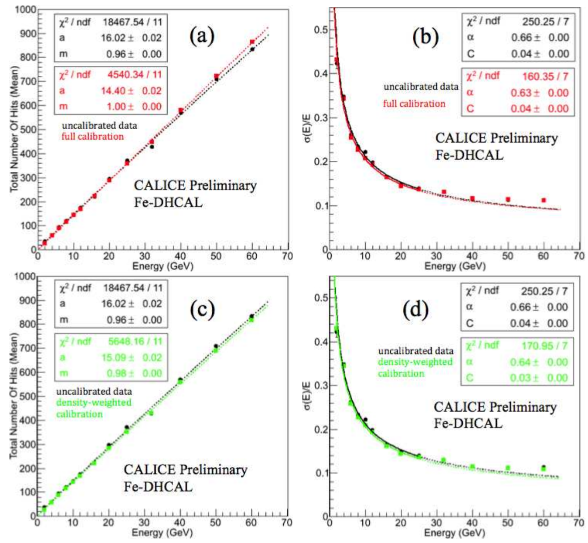

Fig. 3. Mean response (a, c) and resolution (b, d) for the uncalibrated pion data (black), full calibration (red) and density-weighted calibration (green). The fit quality is improved both for mean response (a, c) and resolution (b, d) in the calibrated data compared to the fits to the uncalibrated data. The resolution fits (b, d) are up to 25 GeV (solid) and are extrapolated to 60 GeV (dashed).

Figure 4 shows a picture of a one-glass RPC from the front-end board side (top left) and the pad board side (top right). Also shown are the efficiency (bottom left) and the pad multiplicity (bottom right) measured with cosmic rays. The perfomance of the RPCs is as expected. The Fermilab beam test also indicated that the one-glass RPCs behave as expected when traversed by a hadron shower.

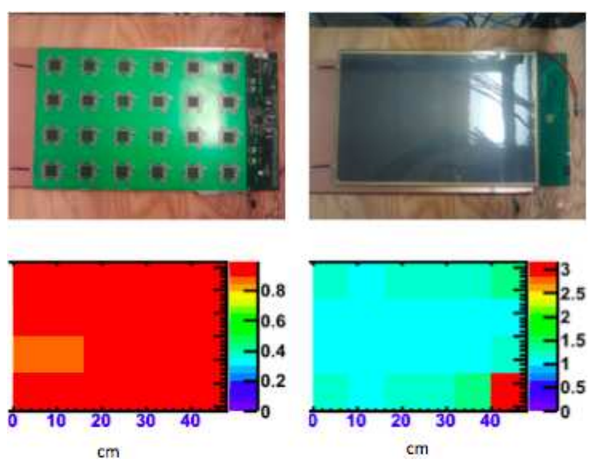

Fig. 4. Pictures of a one-glass RPC (top left and right) and the efficiency (bottom left) and pad multiplicity (bottom right) measured with the cosmic rays.

The rate capability of the RPCs were measured with a stack of four RPCs in the a 120 GeV proton beam of varying intensity at the Fermilab test beam and the results are shown at [4]. The following observations were made:

- No short term inefficiencies with time constants in excess of 0.3 ms were observed.

- At beam intensities in excess of 100 Hz/cm^2, the efficiency is seen to decrease exponentially with time after the beam turns on, until reaching a constant value.
- The time scale for the exponential decrease is of the order of 0.5 second.
- The constant value of the efficiency, reached after the exponential decrease, depends on the beam intensity and is smaller at high rates.
- The beam induced inefficiencies are seen to be local (in the area of the beam spot), rather than affecting the entire chamber.

The rate limitation of the RPCs cannot be classified as a dead time, but it is a local loss of efficiency. The rate capability of the RPCs depends on the bulk resistivity of the resistive plate. With this understanding, we initiated the development of low-resistivity glass in collaboration with COE College, Cedar Rapids, Iowa. Recent developments by the COE College show that resistivities of the order of 10^7 - 10^9 Ωcm can be achieved with iron and copper doped lead vanadates. A first round of production proved the feasibility of the production process and of the possibility of building an operational RPC with these new samples. The second set of samples was also produced and the RPCs built with these samples were tested in the Fermilab test beam for their rate capability. Figure 5 shows the pictures of the second generation low-resistivity glass samples (top right), the RPCs built with these samples (top left) and the Fermilab test setup (bottom).

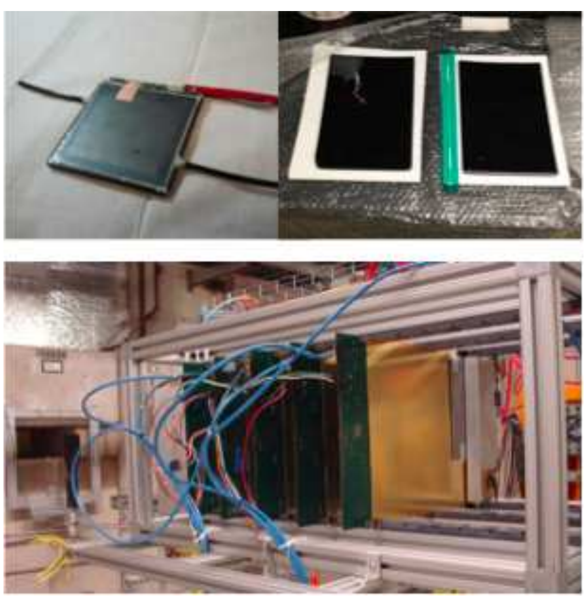

Fig. 5. Pictures of the second generation low-resistivity glass samples (top right), assembled one-glass RPCs (top left) and the Fermilab test beam setup (bottom).

Figure 6 shows the efficiencies as a function of beam rate for two one-glass and three low-resistivity glass RPCs. The one-glass RPC was already measured to have a factor of 2 better rate capability when compared to the default DHCAL RPCs. These tests resulted in a considerable improvement of the efficiency of the RPCs with the utilization of the low-resistivity glass and a clear understanding that the resistivity of the RPC glass can be tuned with high precision in a wide range of possible values. The efficinecy drop for the RPCs with the low-resistivity glass start at higher rates than the one-glass RPC and can maintain around 80% at a 2-3 kHz/cm^2 rate.

The rate limitations of RPCs have been a long standing problem that currently draws a lot of attention in the high energy physics community and the currently studied option is quite promising for a global solution. The new glass is also expected to be available in large sheets and to be affordable, albeit more expensive than the current float glass (but far from the dominant cost of RPCs). Once the study is finalized, the results will constitute a breakthrough in RPC technology, rendering the use of troublesome Bakelite as resistive plates obsolete.

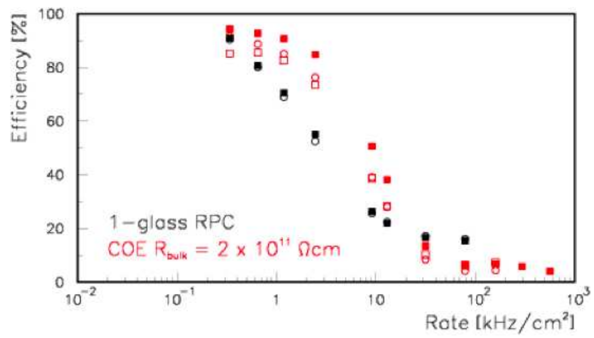

Fig. 6. Efficiency of the one-glass and low-resistivity glass RPCs as a function of beam rate.

B. High Voltage Distribution System

Any large scale calorimeter system will need to distribute power in a safe and cost-effective way. Typical high voltage requirements for such systems are a few kV. HV power supply systems are expected to be able to turn on/off individual channels, tune HV value within a restricted range and monitor voltage and current of each channel. For this purpose, a system based on the Cockcroft-Walton technology is being considered.

The first generation prototype was built and tested with the DHCAL RPCs and the performance was encouraging. This work is currently stopped due to lack of funding.

C. Gas Recycling System

For cost reasons and to protect the environment (from green house gases), the gas used by larger RPC systems, and most of the gases used by various currently operational gas detectors ought to be recycled. For this propose, the development of a new gas recirculation system, dubbed Zero Pressure Containment was initiated.

A recirculation system is a semi-automatic feedback control loop coupled with an analysis/quality control system. Building such a system and getting it to work in a stable equilibrium is a challenge. There are three main "new" aspects to this system.

The first is the purification process, which will involve several types of molecular sieves, activated alumina/copper, activated carbon, and particulate filters (coupled with compressors, regulators). The second is the analysis part, which might include atmospheric analysis, electronegative characterization, possible use of a “canary” chamber, and other more sophisticated tools (gas chromatograph). The third “new” aspect is the manifold of the detectors, which will look very different from what is being used presently.

The manifold of the input and output lines need to be designed in such a way as to maintain a constant pressure difference between the input and output sides. The corrosivity of the exhaust gas makes copper undesirable for long-term use. Therefore, much of the system will need to be made of stainless steel. This system does not yet include any electronic flow controls, which however will be necessary in the future.

Figure 7 shows the schematics of the gas recycling system.

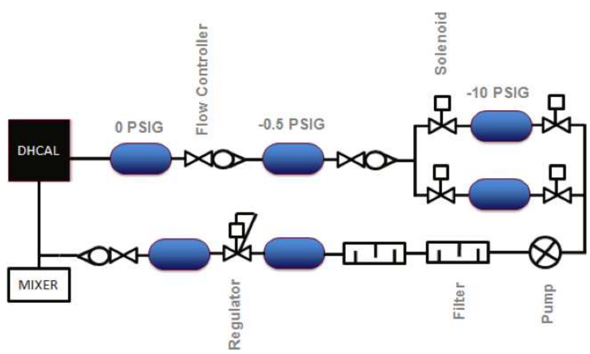

Fig. 7. Schematics of the gas recycling system.

V. Conclusions

The first large-scale Digital Hadron Calorimeter was built and extensively tested in the Fermilab and CERN test beams. This report concentrates on the response to hadrons in the Fermilab test beam.

The DHCAL recorded around 14 million secondary beam events over five test beam campaigns at Fermilab. The beam is a momentum-selected mixture of muons, pions and positrons. Data were collected at various energies form 2 to 60 GeV. The high granularity and the digital readout of the DHCAL enable the utilization of numerous calorimetric tools including but not limited to topological event identification, density-dependent calibration procedures and software compensation techniques.

The calibration of the DHCAL starts with measuring the two performance parameters of the Resistive Plate Chambers: the efficiency and the average pad multiplicity. Although a simple multiplication of these parameters normalized to a reference value can serve, to first order, as a calibration factor, multiple showering particles per pad impact the calibration procedure in a complicated manner. As a result, the density-weighted calibration schemes provide better handles in understanding/manipulating the response differences due to changes in individual RPC performances and operation conditions of the DHCAL. All calibration schemes work equally well in reducing the effect of fluctuations in the performance parameters of the RPCs. The calibration also results in somewhat improved energy resolution.

The R&D on the development of one-glass and low-resistivity glass RPCs has already produced interesting and encouraging results. The rate capability of the RPCs can be significanlty improved by utilizing low-resistivity glass. Furthermore, we have developed tools to fine tune the resistivity of the glass for high rate operations.

The development of a high voltage distribution system and a gas recycling system are important for large-scale detector systems, foreseen in the near future. Prototypes of both systems were tested by the DHCAL group and encouraging results were obtained.

Acknowledgment

The analyses are performed at the University of Iowa High Energy Physics computer cluster GROW and high performance computer clusters NEON and HELIUM.

References

[1] M.A. Thomson, “Particle flow calorimetry and PandoraPFA algorithm”, Nucl. Instrum. Meth. A 611, 25, 2009.
[2] Q. Zhang et.al., “Environmental dependence of the performance of resistive plate chambers”, JINST 5 P02007, 2010.
[3] B. Bilki et.al., “Hadron showers in a digital hadron calorimeter”, JINST 4 P10008, 2009.
[4] B. Bilki et.al., “Measurement of the rate capability of Resistive Plate Chambers”, JINST 4 P06003, 2009.
[5] B. Bilki et.al., “Measurement of positron showers with a digital hadron calorimeter”, JINST 4 P04006, 2009.
[6] B. Bilki et.al., “Calibration of a digital hadron calorimeter with muons”, JINST 3 P05001, 2008.
[7] G.Drake et al., “Resistive Plate Chambers for hadron calorimetry: Tests with analog readout”, Nucl. Instrum. Meth. A 578, 88, 2007.
[8] http://www.hep.anl.gov/repond/DHCAL_FNAL_Nov_2010.pptx
[9] CAN-030, “Analysis of DHCAL Muon Data”, https://twiki.cern.ch/twiki/pub/CALICE/CaliceAnalysisNotes/CAN-030.pdf, 2011.
[10] CAN-042, “The DHCAL Results from Fermilab Beam Tests: Calibration”, https://twiki.cern.ch/twiki/pub/CALICE/CaliceAnalysisNotes/CAN-042.pdf, 2013.