A Digital Hadron Calorimeter with Resistive Plate Chambers

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Concept of a Digital Hadron Calorimeter

Optimized for the application of Particle Flow Algorithms

Trades resolution on a small number of cells (towers) in traditional calorimeters with low (one-bit) resolution on a large number (~$10^7$ – $10^8$) of cells

Novel concept which needs to be validated

Active Element and readout

Resistive Plate Chambers (RPCs)

1 x 1 cm$^2$ readout pads

Collaboration of

Argonne National Laboratory

Boston University

Fermi National Accelerator Laboratory

University of Iowa

In the framework of CALICE

Calorimeter for ILC
Staged Approach

I  Investigation of Resistive Plate Chambers as active elements
II  Development of the electronic readout system
III  Vertical Slice Test with 10-layer prototype calorimeter
IV  Construction of a 1 m³ prototype section
V  Further developments
I Resistive Plate Chambers

Pursued two design options

Two-glass design

One-glass design

Extensive tests with single readout pads, multiple pads, analog and digital readout

Studies completed: RPCs excellent choice for Digital Hadron Calorimetry

The Electronic Readout System

DCAL
- 256 pads, each 1 x 1 cm²
- DCAL ASIC
  - Reads 64 pads
  - Timestamp (with 100 ns resolution)
  - Hit pattern (64 bits)
  - One adjustable threshold

DCOL
- Data Collector
  - Reads up to 12 DCONs
  - VME based

TTM
- Trigger & Timing Module
  - Only one per system

VME bridge

DAQ Computer

J. Butler et al., IEEE transactions (2007)
Performance of the Electronic Readout System

Operation in
Triggered (Cosmic rays, test beam) or Triggerless (Noise measurements) mode

Data push
Dead time free up to ~1 kHz

Gain choices
High gain (GEMs) \{ \text{Low gain (RPCs)} \} \times 5

Noise
Without detector < 4 \times 10^{-5} \text{ Hz/cm}^2

Cross talk
At the 0.3% level
III  Vertical Slice Test

Test of whole system with

Up to 10 RPCs, each 20 x 20 cm$^2$
(Up to 2560 channels)

Test stands

Horizontal for cosmic rays
Vertical for testbeam

RPCs

Up to 9 2-glass designs
1 1-glass design
Thickness = 3.7 mm (chamber) + 4.6 mm (readout) = 8.3 mm

Absorber

For cosmic rays, muon, pions, electrons: Steel (16 mm) + Copper (4 mm)
Rate capability measurement (120 GeV protons): 16 mm PVC with whole cut out in center

Data acquisition

Not fully debugged in the test beam (July 2007)
Now 100.000 % error free!
Digital Hadron Calorimeter: Calibration Procedure

Convert number of hits into the energy of particle

\[ E_{\text{hadron}} = \alpha_{\text{samp}}(\Sigma_i H_i) \cdot \Sigma_i(H_i - B_i) \cdot \left( \frac{\varepsilon_{0}^{\text{MIP}}}{\varepsilon_i^{\text{MIP}}} \right) \cdot \left( \frac{\mu_0^{\text{MIP}}}{\mu_i^{\text{MIP}}} \right) \]

i ... index running over layers
H_i ... number of hits in layer i
\( \varepsilon_{0}^{\text{MIP}} \) ... average MIP efficiency
\( \mu_0^{\text{MIP}} \) ... average pad multiplicity

Data

From testbeam

Number of pads firing for one MIP in layer i

Efficiency for having at least one pad firing in layer i

Average noise rate in layer i

From measurement with MIPs

Monte Carlo

Generate events using \( \varepsilon_{0}^{\text{MIP}} \) and \( \mu_0^{\text{MIP}} \) → see later

Allows for direct comparison with data (at the hit level)
Measurement of Noise Rates

At the default setting the rate measures
~ 0.1 Hz/cm²

For a 5·10⁷ channel calorimeter this rate corresponds to 1 hit in a 200 ns gate

Noise rates
Decrease with increasing threshold
Increase with increasing high voltage

x – y map
Noise rates higher around location of spacers (fishing lines)
Somewhat higher in center (beam activation?)
Calibration with Muons

Explored operating space
Dependence on threshold & HV

Results confirmed earlier studies

Chose as default operating point
HV = 6.3 kV, THR = 110

Efficiency vs. pad multiplicity
2-glass RPCs: results on common curve
1-glass RPC: constant $\mu^{\text{MIP}} \sim 1.1$

$\varepsilon^{\text{MIP}} \sim 90%$
$\mu^{\text{MIP}} \sim 1.5$

B.Bilki et al., 2008 JINST 3 P05001
Monte Carlo Simulation

Simulate avalanches and hit distributions

- Generate **muons** (at some energy) with GEANT4
- Get x,y,z of each energy deposit (point) in the active gaps
- Generate measured charge distribution for each point (according to our own measurements)
- Noise hits can be safely ignored

- Distribute charge according to exponential distribution with slope $a$
- Apply threshold $T$ to flag pads above threshold (hits)
- Adjust $a$ and $T$ to reproduce measured hit distributions

- Generate **positrons** at 8 GeV with GEANT4
- Filter hits if closer than $d_{\text{cut}}$ (pick one hit randomly) (RPCs do not generate close-by avalanches)
- Adjust $d_{\text{cut}}$ to reproduce the hit distribution
- Generate predictions for other beam energies
- Generate **pions** at any beam energy

Final parameters

$a = 0.13$ cm
$T = 0.60$ pC
$d_{\text{cut}} = 0.1$ cm ← only needed for electromagnetic showers (expected to be of the order of the gap size)
Response to Positrons

Preliminary: To be published soon

Data at 1, 2, 4, 8, 16 GeV (electrons selected by Čerenkov)

Response well fit by Gaussian

Accident!

Monte Carlo simulation

Both mean and sigma well reproduced

Large non-linearity

Dominated by leakage out the back (only 6.8 X₀)

Infinite stack – non-linearity due to overlaps in pads

Resolution

Effect of non-linearity ignored in this plot

Infinite stack – should reach 30%/√E at least
Resolution values corrected for non-linearity

Remember → Dominated by leakage
Effect of overlaps (saturation) secondary

Measurement of longitudinal shower shape
Agreement with simulation adequate (at best)
Simulation - Requires additional material in beam line
Response to Pions

Preliminary: To be published soon

Data at
1, 2, 4, 8, 16 GeV (electrons rejected by Čerenkov)

Analysis separates

Non-interacting pions/muons
Pions interacting in first layers
Pions interacting later (rejected)

Exactly one cluster in first layer
Distance $R < 5$
Number of hits in first layer < 5

MIP selection
Number of hits in second layer < 5

Pion selection
Number of hits in second layer $\geq 5$

Gaussian distributions

Nice MIP peaks
MIP selection

Mean and sigma independent of beam momentum
Mean not very well reproduced by simulation
→ Beam contains muons, simulation does not
  (data are cleaner !!!)
Width of distributions adequately reproduced

Pion selection

Measurements at 16, 8 and 4 GeV/c
Not sufficient statistics at 2, 1 GeV/c
Non-linearity due to leakage
Adequate agreement with simulation
IV Construction of a 1 m³ Prototype section

Larger prototype section needed to

- Measure hadronic showers in detail
- Gain experience with larger system
- Compare performance with scintillator approach to granulated calorimetry

Description of the prototype section

- 40 active layers each 1 x 1 m²
- Each layer contains 3 chambers with an area of 32 x 96 cm²
- 1 x 1 cm² pads read out with 1 – bit resolution → 400,000 channels
- Absorber structure and test beam stage from CALICE Analog HCAL

Status

- Larger chambers being tested (32 x 96 cm²)
- Assembly for chamber production and test procedures being developed
- Final touches to design of front-end ASIC → submission in July (engineering run → ~8,000 chips)
- Redesign of pad- and front-end boards → tested successfully
- Redesign of data concentrator ongoing
  (Data Collector and TTM module designs final)

Plan

- Construction of 10 layers by early 2009
- Followed by tests in Fermilab test beam
- Construction of remaining layers in 2009
- Followed by tests in Fermilab test beam
V Further Developments

1 – glass RPCs

Investigation of ways to protect the front-end electronics from sparks
  → Need more than the protection diodes inside ASIC
  (so far has not created problems!)

Front-end readout

Investigation of ways to increase multiplexing

  increase number of channels for the front-end chip
  token ring passing between chips
  ....

Investigation of ways to reduce the thickness of the readout boards

  embedded ASICs, non-packaged ASICs...

Implementation of power pulsing

  tuned to the timing of the ILC bunch crossings
  reduced power consumption
Conclusions

Development of a Digital Hadron Calorimeter for the PFA approach

Resistive Plate Chambers as active elements
Readout pads with an area of 1 x 1 cm²

Resistive Plate Chambers

Investigated both the traditional 2-glass and the exotic 1-glass design
Excellent performance for calorimetry

Vertical Slice Test with Small Prototype Calorimeter

Contained up to 10 RPCs
Tested entire readout chain
Very successful
Calibration with muons → B.Bilki et al., 2008 JINST 3 P05001
Response to positrons → To be published soon
Response to pions → To be published soon
Rate capability measurements → Data not yet analyzed

1 m³ prototype section

Preparing for construction
10 – layer stack by early 2009
Complete 40 – layer stack later in the year

Reasonable agreement with simulation

Validation of concept of Digital Hadron Calorimetry