5/22/2009

Calibration of a Digital Hadron Calorimeter with Resistive Plate Chambers as Active Media

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1. Introduction

This note describes the calibration procedures for a Digital Hadron Calorimeter (DHCAL) with Resistive Plate Chambers (RPCs) as active media. The calorimeter is assumed to be part of a multi-purpose detector, which has been optimized for the application of Particle Flow Algorithms (PFAs) for the reconstruction of the energy of hadronic jets at the International Linear Collider (ILC). In this context the primary role of the hadron calorimeter is to provide a measurement of the energy of neutral hadrons in hadronic jets.

The readout of the RPCs is assumed to be segmented into 1 x 1 cm^2 pads, which are read out individually with a resolution of 1-bit (digital readout). With this fine granularity of the readout, the entire DHCAL will count approximately $5 \cdot 10^7$ readout channels.

The following outline of a calibration procedure is based on the use of 2-glass RPCs, which feature a pad multiplicity larger than one for single minimum ionizing tracks traversing the chamber. The calibration procedure for 1-glass RPCs is similar, but simplified by their constant pad multiplicity close to unity. The time estimates for monitoring (see below) the performance of 1-glass RPCs is significantly reduced compared to the requirement for 2-glass RPCs.

2. Reconstruction of the energy of a shower

The event record for the DHCAL will contain a list of hits and their location. It is assumed that an algorithm, e.g. a PFA, assigns subsets of these hits $\sum H_i$ to individual hadronic showers. The energy E_h of such a shower will be reconstructed as

$$E_h = \alpha_{sampl}^h \times \sum_i \left[\left(H_i - B_i\right) \times \frac{\varepsilon_0}{\varepsilon_i} \times \frac{\mu_0}{\mu_i} \right]$$

$$= \alpha_{sampl}^h \cdot \varepsilon_0 \mu_0 \times \sum_i \frac{H_i - B_i}{\varepsilon_i \mu_i}, \qquad (Eq.1)$$

where

H_i … are the hits in layer i assigned to a given shower, where i runs over all layers of all modules of the DHCAL,
α^h_{sampl} … is the sampling term, which may depend on ΣH_i,
B_i ... is the average contribution from noise in layer i of the geometrical area of the shower,
ε_0 … is the average MIP detection efficiency of all RPCs in the calorimeter,
ε_i … is the actual MIP detection efficiency of layer i,
μ_0 … is the average pad multiplicity for a MIP of all RPCs in the calorimeter, and
μ_i … is the actual pad multiplicity for a MIP in layer i.

3. Calibration constants

Equation 1 contains six calibration constants/variables. Of these three constants (α^h_{sampl}, ε_0, μ_0) are time-independent and three variables (B_i, ε_i, μ_i) may vary with time. Whereas the time-independent constants need to be determined only once as part of the calorimeter's calibration procedure, the time-dependent variables need to be monitored during the entire data taking period.

4. Choosing of an operational setting

The response of RPCs was studied in detail with cosmic rays [1] and with muons in the Fermilab test beam [2]. Figure 1 shows the measured pad multiplicity μ as a function of the MIP detection efficiency ε. In this type of measurement both the high voltage and the threshold setting were varied to obtain a given MIP detection efficiency. In subsequent tests with positrons [3], pions, and protons [4] the chambers were then operated with a high voltage setting of 6.2 kV and a threshold of 110 counts. This resulted in an average efficiency of 90% and a pad multiplicity of 1.5.

A similar procedure will be followed at the ILC. The response of individual chambers will be determined either with cosmic rays or with muons from a test beam. The high voltage settings of the chambers and/or the threshold of the readout will be adjusted to yield the default MIP detection efficiency ε_0 and the default pad multiplicity μ_0. These values of ε_0 and μ_0 will remain constant for the life of the experiment and will be utilized in the Monte Carlo simulation of the response of the chambers[1]. If necessary, adjustments of the high voltage setting of individual layers or of the readout threshold will be used to compensate for possible long-term drifts in ε_0 and μ_0.

[1] Whereas systematic variations of the response over the area of RPCs (such as due to dead areas) will be incorporated into the simulation, overall variations in the response of different RPCs will not be simulated.

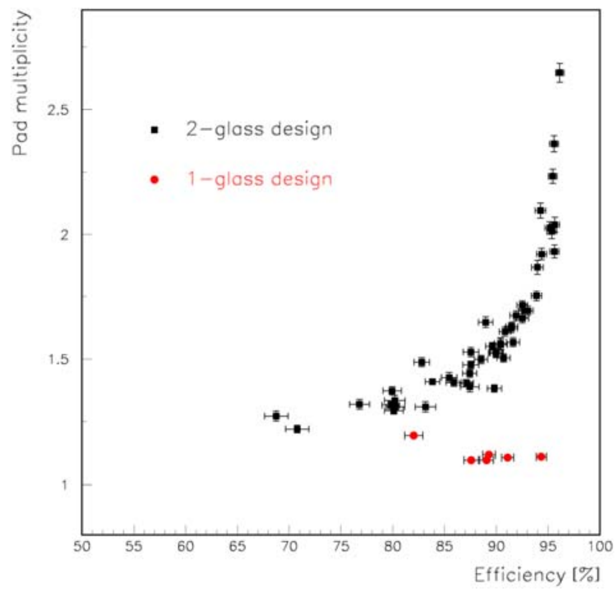

Figure 1. Pad multiplicity versus MIP detection efficiency as measured with muons at the Fermilab test beam. The black (red) dots correspond to chambers with 2-glass (1-glass) plates.

5. Determination of the sampling term

The sampling term α_{sampl} will be determined in a three step procedure. The procedure takes into account the possibility of different sampling terms for charged pions and neutral hadrons:

a) Modules will be exposed to pion test beams of varying energies, providing a measure of

$$H_{measured} = \sum_i \{(H_i - B_i) \times \frac{\varepsilon_0}{\varepsilon_i} \times \frac{\mu_0}{\mu_i}\}$$

The sampling term for pions will be determined as

$$\alpha^{\pi}_{sampl}(\sum H_i) = E_{beam} / H_{measured}$$

where the dependence on ΣH_i allows to correct for a possible non-linearity of the response.

b) The response of the modules to charged pions will be simulated and compared to the measurement, thus validating the simulation of hadronic showers.

c) The response of the modules to neutral hadrons will be simulated and the sampling term for neutral hadrons will be determined as

$$\alpha_{sampl}^{h^0}(\sum H_i) = E_{generated} / H_{simulated}$$

In principle, the sampling term for neutral hadrons could also be determined in a tagged neutral hadron beam. However, this might not turn out to be practical, due to the associated experimental challenges of such a measurement.

6. Measurement of the background rate

The background rate can be measured utilizing the self-triggered mode of the front-end readout. Measurements on the prototype chambers typically showed a background rate of 0.1 – 0.2 Hz/cm^2. As an example Fig.2 shows the noise rate as function of high voltage setting for a threshold setting of 110 counts.

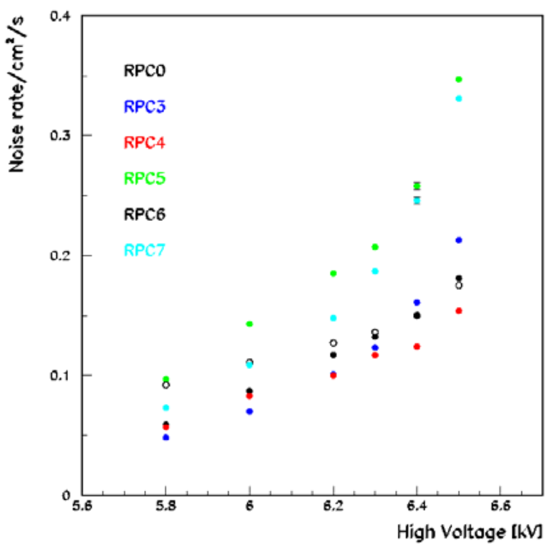

Figure 2. Noise rate as function of high voltage for six different chambers. The threshold was set at the default value of 110 counts. The default high voltage setting for measurements with positrons, pions and protons at the FNAL test beam was 6.2 kV.

Assuming a gate width of 300 ns and a total of $5 \cdot 10^7$ readout channels, the expected noise rate at the ILC will be about 2 hits/event in the entire DHCAL. Assuming a calibration of 13.6 hits/GeV, as obtained in recent simulations of the DHCAL, the noise contribution corresponds in average to around 150 MeV/event and can be ignored for all practical purposes.

Beam related background rates, due to neutrons for instance, will be measured using bunch-crossing events and algorithms for separating energy deposits from e^+e^- -collisions and from beam backgrounds.

7. Monitoring of individual chambers

Under fixed operating conditions (high voltage and threshold setting) the performance of RPCs depends on a) the ambient temperature, b) the atmospheric pressure and, for completeness, c) the gas flow. The latter only impacts the noise rate and the pad multiplicity. However, above a minimum gas flow these are seen to be constant and do not depend on variations of the flow. The performance of the RPCs does not depend on the ambient air humidity[2].

The dependence on the environmental conditions can be parameterized [5] as

$$\begin{aligned}\Delta\varepsilon &= [-0.06\cdot\Delta p(100Pa)+0.3\cdot\Delta T(^0C)]\% \\ \Delta\mu &= [-0.25\cdot\Delta p(100Pa)+2.0\cdot\Delta T(^0C)]\%\end{aligned} \qquad (Eq.2)$$

Figure 3 shows the results of the monitoring of two RPCs over the time span of nine months. The fluctuations in ε are seen to be quite small. The large increase in noise rate and pad multiplicity observed in November – December 2008 is due to operation of the chambers with a drastically reduced flow rate.

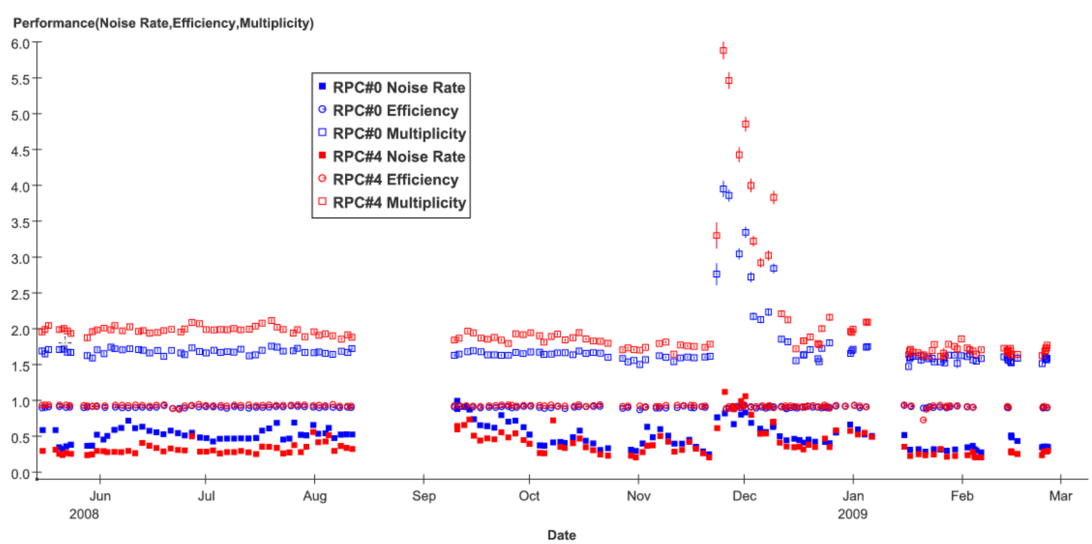

Figure 3. Monitoring the noise rate, MIP detection efficiency and pad multiplicity of two chambers for a period of nine months. The large increase observed in November – December was due to a drastically reduced gas flow. The chambers were operated at reduced readout thresholds, compared to the default value of 110 counts.

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[2] This is true for glass RPCs. With Bakelite as resistive plates the performance depends on the humidity of the surrounding air, as well as on the water content in the gas mixture.

In the following we assume that the changes in performance are uniform within an entire chamber. Two methods will be employed to monitor the chamber's performance. One utilizing track segments in events from ILC collisions and the other utilizing cosmic rays.

a) Track segment monitoring

Imaging calorimeters offer the possibility to reconstruct individual track segments within hadronic showers [2] or in $e^+e^- \rightarrow \mu^+\mu^-$ events. Such track segments can be used to monitor the MIP detection efficiency ε_i and the pad multiplicity μ_i of individual layers during the data taking period.

For a 3% measurement of $\varepsilon(\mu)$ 100 (1,000) measurements are needed. Assuming a cross section of 4,700 fb for qqbar events at $\sqrt{s}$ = 500 GeV, an average integrated luminosity of 1 fb^{-1}/day produces 9,400 hadronic jets per day. Further assuming that each jet produces on average one usable track segment per layer in the DHCAL, with 8x3 barrel modules and 2x4 endcap modules, a 3% precision is achieved within a 5 day period.

In addition, data corresponding to an integrated luminosity 1 fb^{-1} will contain about 20,000 muons with energy above 10 GeV per DHCAL module. So, even at 1% of the design luminosity a 3% precision appears feasible within approximately 5 days.

b) Cosmic ray monitoring

Cosmic rays are an ideal tool to monitor the performance of the chambers. At sea level the flux through a horizontal surface is ~ 1 $cm^2 min^{-1}$. Burying the detector underground and requiring momenta above 10 GeV/c reduces the flux to approximately 0.05 $cm^{-2}min^{-1}$. With this flux horizontal chambers with an area of 2 m^2 obtain 1000 measurements per minute. The rate in vertical chambers will be reduced by say one order of magnitude. Nevertheless, the required precision of 3% can be obtained in less than one hour.

However, if the front-end power is pulsed, this will lead to a reduction in duty cycle of up to a factor of 200. In this case, time estimate needs to be increased to approximately 1 week. Further studies are needed to understand the cooling needs of the DHCAL and to define the optimal duty factor, taking into account the need for monitoring the performance of the RPCs.

c) Correcting for environmental changes

In long-term studies of prototype RPCs, the efficiency and pad multiplicity were seen to vary by ±0.9% and ±5%, respectively. Applying corrections for the environmental conditions (i.e. ambient temperature and air pressure) based on Eq. 2 reduces these variations to ±0.8% and ±3%.

d) Effects of uncertainties in the calibration

Based on detailed simulations of the response of RPCs the effect of uncertainties in the calibration on the measurement of single particle energies was estimated. The studies showed that, for instance, for 10 GeV π^+ the energy resolution degrades by approximately by 1%, if the entire module's response is smeared by a Gaussian distribution with a sigma of 3%. This is the worst case scenario, where the responses of all layers in a given module are 100% correlated. If, on the other hand, all individual layers in a module fluctuate independently say by a Gaussian distribution with a sigma of 3%, the effect on the energy resolution is negligible.

8. Combining ECAL and DHCAL data

The combined response of the ECAL and DHCAL to charged pions will be studied in test beams in the summer of 2010. After validation of the hadron shower models, the simulation will be used to study the combined response to neutral hadrons and to develop reconstruction algorithms giving the best possible energy resolution. In particular, the possibility of treating the ECAL data as a collection of hits (similarly to the DHCAL and ignoring the analog information) will be explored.

The combined response to charged pions will also be studied at the ILC, where tracking information will provide a precise momentum measurement. Even at 1% of the design luminosity the charged particles rates will be sufficient for initial studies of the combined response as function of angle and energy.

9. Leaking electromagnetic showers

The combined response of the ECAL and DHCAL to electromagnetic showers (leaking into the DHCAL) will be studied in the test beam in summer 2010. The data will be used to develop reconstruction algorithms providing the best possible energy resolution,

10. Cross checks at the ILC

The overall energy scale of the jet reconstructed at the ILC will be cross checked using 2-jet events and reconstructed $W^{\pm}$ and Z^0 boson masses. At $\sqrt{s}$ = 500 GeV with an integrated luminosity of 1 fb^{-1}/day we expect to collect 2,800 (1,900) 2-jet (W^+W^-) – events/day. With enough statistics the dependence of the reconstructed jet energy on the electro-magnetic fraction of a jet or the fraction of neutral hadrons in a jet can be studied.

11. Summary

The calibration and monitoring of the DHCAL is possible using the combination of test beams, simulations, track segments and cosmic rays. At the ILC, the reconstruction of 2-

jet events and $W^{\pm}$ boson masses will provide an important cross check of the calibration and monitoring procedure. No dedicated running at the Z^0 is necessary for either calibrating the DHCAL or for monitoring its performance.

References

[1] G.Drake et al., Nucl. Instr. Meth. **A578**, 88 (2007).
[2] B.Bilki et al., 2008 JINST **3** P05001.
[3] B.Bilki et al., 2009 JINST **4** P04006.
[4] B.Bilki et al., arXiv : 0901.4371, to appear in JINST
[5] Paper in preparation.