Semi-Digital Hadronic Calorimeter for Future High Energy Physics Experiments

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Abstract. A new concept of high granularity hadronic calorimeter based on a semi-digital readout for future ILC experiments is presented. The aim of this concept is to provide the HCAL with a tracking capacity in addition to a good energy measurement resolution. The sensitive medium of this HCAL is made of very thin gas detectors. The readout is based on detector-embedded electronic boards equipped with low consumption daisy-chained 64-channel chips. The nice results obtained with a slice test made of small detectors show that the concept is successful and can be used to build a 1m3 semi-digital HCAL prototype.

1. Introduction
One of the most promising techniques that the next generations of high energy physics experiments are likely to exploit is the one based on particle flow algorithms. The concept uses the fact that better jet energy resolution can be achieved when jet particles are tracked down in the different sub-detectors. The idea behind this is that if the particle is tracked in all the sub-detectors, then its energy can be estimated in the most suitable one obtaining thus the best possible measurement.

To achieve this goal the different sub-detectors should be able to have a tracking capacity in addition to their own specific job. This means that future calorimeters should be modified to allow tracking particles in addition to the energy measurement. The statement is valid for both the electromagnetic and the hadronic calorimeters [1]. Following this idea we present here a new generation of hadronic calorimeters with high granularity in both the transverse and the longitudinal directions offering tracking capacities.

To cope with the tremendous number of electronic channels associated to this kind of calorimeter, a new generation of electronics has been developed. The new electronics is detector-embedded with daisy connection scheme. It provides a semi-digital readout while reducing the power consumption by a factor of 100 thanks to the power pulsing mechanism it offers. Different gas detectors are proposed to provide the sensitive media for this new generation of hadronic calorimeter. Glass Resistive Plate Chamber is one of those candidates which associate high performance to low cost production.

In this paper we first introduce the semi-digital hadronic calorimeter concept. We then present the new electronics and the readout system that was developed for this purpose. We then describe the GRPC detector that we used as a sensitive medium to build our test setup. Finally we describe the setup and the first results obtained with the new concept.

2. Semi-Digital Hadronic CALorimeter concept:
The standard hadronic calorimeter using scintillators as sensitive media can perform high precision energy measurement [2]. However, it may suffer from its poor transverse granularity due to the size of
scintillators that can be used in this kind of detector. This may become an important limitation factor when it comes to the PFA application.

To overcome this limitation a digital hadronic calorimeter with high granularity was proposed within the CALICE collaboration [3] with the aim to attain high transverse granularity (1 cm$^2$) To achieve this, the analogue readout usually used in the standard HCAL is traded against a binary one and the scintillator is replaced by gas detectors adequate for high granularity sensitive media realisation.

Although this digital HCAL with its high granularity structure is well suited for the PFA application, one may think that the binary readout can affect the energy resolution the HCAL is able to provide. This is not true at low energy. Indeed, up to few GeVs, the simple counting of the hits left by the hadronic shower in the HCAL gives very good estimation of the primary particle energy. The energy resolution obtained in this case is even better than in the case of the analogue readout which suffers from the Landau fluctuation. When the energy becomes high either in the case of a single particle or a jet the particles density in the shower central region becomes higher and a simple counting of the hit numbers does not allow one to establish a good correlation between this number and the number of shower particles and hence prevents to achieve good energy measurement resolution.

A way to improve on the high energy resolution while keeping the high granularity of such a calorimeter can be obtained by going from binary readout to a semi-digital one. Replacing one-bit readout by two-bit readout can be of big help. It allows one to distinguish between the simple case with one particle going through one pad of the detector and the cases where few or many particles going through a detector pad.

A work realized by a KEK group [4] has shown that with such a readout one can have three thresholds which may be fixed for instance to (0,5, 10 and 100 mip energy). The energy measurement resolution obtained in the case using scintillator sensitive medium is as good as the one obtained with the analogue readout.

In order to prove the validity of the semi-digital HCAL concept in the context of the future international linear collider experiments, we conceived and realized a new ASIC. We also conceived and built electronic boards capable to host four ASICs. The boards were then associated to GRPC detectors. A readout system was also developed and the whole system was tested using a cosmics bench.

3. Sensitive medium for the DHCAL

Increasing the granularity of the HCAL necessitates a new gender of sensitive media with a transverse segmentation as small as 1 cm$^2$. In addition, the thickness of such a medium should be very small to have the most compact HCAL. This is motivated by the fact that the HCAL is expected to be inside the coil of the future ILC experiments. Different gas detectors can satisfy those requirements like the Glass Resistive Plate chamber [5], the Gas Electron Multiplication chamber [6] and the MICRO MEsh GASEous chamber [7]. The thickness of such detectors can be of only few millimetres. Many efforts are underway to adapt them to the DHCAL concept. Here after we describe the GRPC that was used to validate the semi-digital HCAL concept.

The GRPC proposed for the semi-digital HCA is made of two thin glass plates separated by spacers which can be of different shapes. Fishing lines are the standard spacers. An ionising gas is enclosed inside the two plates. High voltage is applied to the two plates through a very thin layer of resistive painting on the outer side of the plates. The resistive painting used is usually made of graphite (less than 1M \(\Omega/\mu\)). A thin Mylar layer separates one of the glass plates from the electronics card which contains on the inner face the 1 cm$^2$ cooper pads.

When a charged particle crosses the chamber, it ionises the gas and a shower is produced. The electrons of the shower are attracted to the glass connected to the anode. They induce opposite charges on the pads of the electronics card producing thus the signal.

According to the nature of the ionising gas and the high voltage value one can obtain an avalanche mode or a streamer mode. The streamer mode produces an important quantity of charge whose
evacuation from the glass plate takes more time and thus reduces the detector rate capability (not more than few Hz/cm$^2$).

The avalanche mode is more appropriate for the future ILC hardonic calorimeter. The amount of produced charge is a factor of 100 less which implies a detection rate that can go beyond 100 Hz/cm$^2$. The gas which is usually used to obtain the avalanche mode is a mixture of the TFE (93%), the isobutene (5%) and the SF$_6$ (2%). The last two gases are used as photon and electron quencher respectively to keep the signal localised around the crossing article.

4. Electronics readout system

The high granularity HCAL necessitates also to readout a tremendous number of channels. This leads to two major technical challenges that the electronics readout has to tackle. The first is the power consumption. With up to fifty millions channels needed to readout a hadronic calorimeter like the one expected for the future ILC experiments [8] it is of a primary importance to reduce the power consumption to the lowest level. The second challenge resides in the number of connection needed for this enormous number of channels. This involves an unthinkable quantity of cables to be used and whose effect on the detector geometry can result in many cracks and holes preventing the detector from being hermitic which renders the PFA application much less efficient. To solve these two problems a new electronic chip (ASIC) called HARROC [9] was developed. It can deal with 64 channels each of them having two independent comparators to provide two thresholds. The thresholds can be fixed by software to integer values in the interval between 0 and 1023 (DAQ units). An important feature of this chip is the power pulsing. It allows the chip to be active just before the bunch crossing and off just after. This permits to reduce the power consumption by a factor of 100 in the case of the ILC cycle machine which is supposed to last 200 ms of which only one millisecond is reserved for the bunch crossings. The chip is conceived to be very tiny so it can be embedded on the detector. It has the advantage to be connected to other chips through the daisy chain mechanism so that the chips of the same detector plan can communicate with each other. Slow control parameters as well as data collected in the detector can then circulate among the chips while the communication with the outside acquisition system is hugely reduced. In addition to these features, the chip has an internal memory capable to contain up to 128 events. The aim of this memory is to record the events which occur during the bunch crossing and then read them out during the idle time. This means that during the bunch crossing the chips are able to record all the signals and hence no event can be lost because of online selection. Of course this is possible due to the low occupancy rate expected in the HCAL of the future ILC experiments. Another feature of this ASIC is the possibility to change the gain of each channel in the interval [0-4] with a 6-bit precision. This is a useful tool to render the response of the different channels to the same signal as identical as possible. The cross-talk between two channels of one ASIC was measured by injecting an electric signal equivalent to the one produced by the average charge left by a mip (1 pc) in a GRPC through one channel using an appropriate test board. The signal observed in the other channels was found to be less than 2%. In figure1 a synoptic presentation of the HARDROC chip is shown.
Figure 1: Synoptic scheme of the HARDROC chip

To validate the concept of a semi-digital hadronic calorimeter with high granularity, a Printed Circuit Board was conceived to host 4 hardroc chips and to provide the connection between adjacent chips as well as the connection of the first chip to the readout system. For simplification reasons the readout system using FPGA device was also implemented on the same PCB as well as a USB device responsible of the communication between the FPGA and a computer. The PCB is an 8-layer circuit with two internal layers reserved for the digital signal transfer. The routing was optimised to reduce the cross-talk among adjacent pads. The thickness of the PCB is only 800 microns to keep the effective detector thickness as small as possible. On one of the two PCB faces, 256 cooper pads of 1X1 cm$^2$ were printed. The distance between two adjacent pads was chosen to be 500 microns. This was intent to allow the charged particles which cross the detector between two pads to be detected at least by one of the two pads since the spread of the produced shower at the anode level is expected to be around 1 mm$^2$. The pads are connected internally to the ASIC channels through the PCB structure. The cross-talk among adjacent pads was tested before other electronics components were fixed on the PCB by injecting a charge of 1 pc on one pad using an appropriate probe. The charges induced on the adjacent pads were then measured and found to be less than 0.3 % of the injected one which means that the cross-talk due to the PCB is negligible with respect to the ASIC one which is itself very small. Acquisition software was also developed. It permits to download the different slow control parameters to the different ASICs and to collect data from these ASICs through the FPGA device. Two readout modes were implemented. The first one is the ILC-Like one where events are recorded during the bunch crossings and the readout takes place after. The other mode was conceived for cosmics and beam test studies. In this mode the acquisition and data taking is stopped when an external trigger occurs. The memory of the different ASICs is then read out. In both modes each event is associated with a time stamp. In the external trigger mode the time difference between the external trigger and the last recorded event is also given. This determines the time occurrence of each event with respect to the external trigger one.

5. Experimental setup
Few GRPC detectors of 33.55 X 8.35 cm$^2$ each were built and associated to the PCB hosting the ASICs as well as the readout system. Three of the fully equipped detectors were placed in a mechanical structure and oriented horizontally so they can detect cosmics. A system of three
scintillators associated with PhotoMultipliers was built to form a trigger system for the cosmics crossing the detectors (figure 2). A software graphic interface based on LABVIEW was elaborated. The interface was used to calibrate the lower threshold of the 256 channels of each of the three electronics boards. Indeed a charge of 100 fc was injected through internal capacitors to each channel one by one for different values of gains. Each step was repeated 100 times to accumulate significant statistics. For each gain value, the response of the studied channel was recorded and an efficiency curve called (Scurve) was obtained by varying the lower threshold by a step of 1 DAQ unit. An automatic procedure using a fit with a Dirac-Fermi function leads then to determine the inflexion point (corresponding roughly to the 50% efficiency level) for each channel and for each gain. The correlation between the gain and the inflexion point DAQ values was then found to be linear and was fitted by a straight line. The operation was repeated for the 256 channels of each detector. The average value of the 256 inflexion points obtained with gain = 1 was then selected as a reference value. Then for each channel the gain was chosen according to the aforementioned study so that the new inflexion value was as close as possible to the reference value. Once all the gains are corrected, the Scurves were produced again. Figure 3 shows the dispersion of the inflexion points obtained before and after the gain correction. After the gain correction the dispersion of the 256 channels is less than 1.3 DAQ units. This represents a dispersion of less than 2.6 fc in charge values. Indeed, to determine the correlation between the DAQ unit and the injected charge, charges with different values were injected and the inflexion point value determined at gain = 1. This allows one to find the correspondence between the charge and the DAQ units which appears to be: 1 fc = .48 DAQ units.

Figure 2: The test setup
After the gain corrections applied to the three PCBs the whole system was mounted. An external trigger provided by the scintillator-PM system permits to stop the acquisition of the three of them when a cosmic was signalled. The data recorded in the 12 ASICs is then read and the events (hits) which occurred in the time window corresponding to the signal time arrival with respect to the external scintillator are considered for efficiency and multiplicity studies. The time window was estimated using the measured time difference between the analogue signal obtained from the cathode side and the trigger signal. It was then confirmed by the results obtained on the anode side. The width of the time window is taken to be of 200 ns which is the resolution given by the internal ASIC clock of 5 MHz.

The efficiency and multiplicity was first obtained by observing the presence of hits in the time window mentioned above and their number for different values of the high voltage. The results are shown in figure 4 for a standard GRPC detector (graphite painting and fishing line spacers) which are in agreement with the results found using standard electronics. Other detectors using more resistive painting (LICRON) and more sophisticated gas distribution inlet as well as ceramic microspheres as...
spacers were studied using the same dispositive. These modifications lead to an important reduction of the multiplicity as shown in figure 5. It goes down from 1.6 to 1.3 at 7.4 kV. This is an important result since the multiplicity of a mip should be close to one in order to have the best tracking precision. In order to study the noise effect on the previous results the same study was realised using shifted time windows. The results obtained indicate that the noise contribution to the measured efficiency is negligible. The noise was also measured independently by counting the number of recorded hits by time interval in each channel for different high voltage values. In the worst scenario which takes place for high voltage values (>7.5 KV) and low threshold value (< 100 fc) the noise is less than 1 Hz/cm² which is ridiculously irrelevant when considered within the 300 ns time interval during which one bunch crossing is expected to take place in the future ILC and during which the acquisition system is active.

Although the two thresholds were present for the recorded events, only the first threshold was considered for the time being. The hits obtained using the second threshold, were however checked to be included in the set of those obtained with the lower threshold and their number decreases with the increase value of the threshold. The information provided by the second threshold will be soon used when the setup is exposed to a beam at CERN during this summer in order to study its effect on the tracking precision as well as the energy resolution.

Figure 5: Efficiency (left) and multiplicity (right) versus H. Voltage values of a GRPC with LICRON painting (threshold = 100 fc).

The efficiency and the multiplicity versus high voltage studies for each of the GRPC detectors were redone using the information from the other two GRPCs. This allows one to obtain more precise results since the hits position in the studied detector can be predicted from the ones recorded in the other detectors. The results obtained confirmed the previous ones.

6. Conclusion
The semi-digital HCAL concept proposed for the future ILC can be a powerful tool to apply the PFA techniques through the high granularity it offers. The use of 2-bit readout rather than a binary one (1-bit) can help to keep the energy resolution close to the one of the analogue one especially when the charge spectrum associated to a mip in the GRPC is less spread. This can be in fact achieved by going from simple to multigap GRPC [10].

The electronic readout system was designed and realised. A cosmics bench test was built and fully equipped GRPC detectors were tested. The first results show that the concept is successful. Yet, many efforts are underway to improve on both the detector and the electronics performance. A mini hadronic calorimeter made of five GRPC detectors separated with iron slabs of 2 cm each is already built. Beam tests programmed this summer at CERN will permit to provide more hints on the way to improve the performance of the semi-digital concept.
The success of the tests already realised and those to come will lead to the construction a hadronic calorimeter prototype of 1m³ in the coming two years.

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