Test beam studies for a highly granular GRPC Semi-Digital HCAL

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Abstract. The Particle Flow Analysis approach retained for the future ILC detectors requires high granularity and compact particle energy deposition. A Glass Resistive Plate Chamber based Semi-Digital calorimeter can offer both at a low price for the hadronic section. This paper presents some recent developments and results near test beam in the use of Glass Resistive Plate Chamber with embedded front-end electronics to build a prototype based on this principle. All the critical parameters such as the spatial and angular uniformity of the response as well as the noise level have been measured on small chambers and found to be appropriate. Small semi-conductive chambers allowing for high rates and a large chamber have also been tested.

1. Case for a GRPC Semi-Digital Gaseous Hadronic Calorimetry
The Particle Flow Analysis (PFA) approach [1], retained for all the detector concepts in development for the future International Linear Collider (ILC), requires calorimetric systems able to spatially separate the contributions from the individual particles constitutive of a jet. The key feature of calorimeters then shifts from the best energetic resolution in response to individual particle to the best spatial resolution. This paradigm is pushed at its limit in the case of digital calorimetry, where a single bit summarises the energy information for each cell.

A digital hadronic calorimetry has long been discussed [2, 3]. Some recent GEANT4 [4, 5] based studies on a Scintillator-Lead calorimeter [6] have shown the feasibility, using 3 thresholds (“two bits”) and cell lateral sizes of 1 × 1 cm², to reconstruct the energy of single charged pions, up to 100 GeV, with an energy resolution comparable to the one obtained using an analog readout (“many bits”).

The use of a gaseous, hydrogen poor, planar sensitive medium presents many advantages for a digital calorimetry. The main ones are:

- their insensitiveness to the dispersed, delayed and usually relatively badly measured neutron component of hadronic showers, resulting in narrower shower: typically a 100 GeV pion is expected to be contained at 99% in a stainless-steel gas calorimeter of section 70 × 70 cm² [7].
- the ease to adjust the readout pad size to very small value if desired;
- more specifically for single Resistive Plate Chambers (RPC), the proven possibility to make large surface, robust and reliable sensors at very low cost.

Among the many available techniques usable for large surface gaseous sensors, 3 are now being studied in the CALICE collaboration: MicroMEsh GAseous Structure (MicroMegas) and
Gas Electron Multiplier (GEM) in which the ionisation electron signal is amplified by a mesh after a drift, and GRPC (Glass Resistive Plate Chamber), in which the amplification occurs immediately; this article focuses on the later.

The efficiency ($\epsilon$) and cell multiplicity ($\mu$) in response to minimum ionising particles are the two critical parameters required for the intercalibration of the channels of a (semi)digital calorimeter. They should be supplemented by the understanding of the response to a full hadronic shower, which might affect the sensor itself or the embedded electronics. Finally, although this should not be a problem at the ILC, the recovery time for various spatial scales and intensity, have to be measured, as well as the sensitivity to high magnetic fields.

Technologically, the use of RPC in a large hadronic calorimeter faces a few challenges, which should be integrated as early as possible in the conception. The first is the industrial production and handling of large surface, uniform sensors at low cost. To keep compact showers, the ratio of low density material to absorber should minimised, requiring thin sensitive and readout layer. Practically, the goal is to reach 6 mm all inclusive (RPC and electronics) for 20 mm stainless steel absorber.

Such devices have been produced in various sizes and the present paper describes the test setup in test beam and the results obtained: the aim is to validate the whole embedded electronics readout system in beam conditions (including the use of local data storage and train reconstruction), to study the GRPC behaviour as a function of the applied HV and thresholds, of incoming particle angle, position, rate and to validate the technological choices prior to the construction of a full scale 1 m$^3$ prototype [8].

2. Glass RPC prototypes with an embedded readout

The results shown here were obtained with various prototypes sharing the same geometry: a gap of 1.2 mm of gas between two glass plate, polarised under a nominal voltage of 7.4 kV. The gas used was a mixture 93% of TetraFluoroEthane (TFE), 5% of Isobutane and 2% of Sulphur HexaFluoride (SF6) yielding 8 primary ionisations per mm of a mip track. The glass plates, respectively of 1100 and 700 $\mu$m thickness for the cathode and anode sides, are separated by Nylon fishing lines and covered on their external sides by a resistive coating.

Three types of coating were used: Graphite, Statguard® and Licron® yielding resistivity of respectively 0.4, 2 and 20 M$\Omega$/☐.

Small chambers of 8.35 $\times$ 33.55 cm$^2$ were built using either standard float glass, in combination with the 3 types of coating, or semi-conductive glass with Licron and Statguard coatings. Large chambers of 1 $\times$ 1 m$^2$ were built out of float glass coated by colloidal graphite (having resistivity of 1-2 M$\Omega$/☐).

In order to read efficiently many channels, the very front-end part of the readout electronics is integrated in the detector itself: the readout ASICs and their supporting PCB, are only separated from the anode coating by a 50 $\mu$m insulating layer of Mylar®.

With a capacity of 64 channels, the HaRDROC [9] (Hadronic RPC Detector Read Out Chip) specifically developed by the Omega micro-electronics group of Orsay, has 2 independent
adjustable thresholds (above 10 fC) used for auto-triggering. It can store up to 127 events composed of an 8-bit ASIC ID (8 bits), a time stamp (24 bits by steps of 200 ns) and the hit map (2 × 64 bits). Each channel gain can be adjusted over a range 0–4 on 6 bits. Its internal inter-channel cross-talk has been measured to be below 2 %.

Some test boards holding 4 HaRDROC’s and their control and readout logic, were produced and tested in 2007. They feature 8-layer, 800 µm thick PCB with buried and blind vias, ensuring cross-talk below 0.3 %, and the readout of 8 × 32 pads of 1 × 1 cm², separated by 0.5 mm gaps. First used to validate the new electronics and acquisition scheme, they then served for the beam tests equipped with GRPC sensors, as described hereafter.

The relative gain of the individual channels of each ASIC were first adjusted by levelling the threshold responses to 100 fC injected charges. A factor of 4 was gained on the built-in spread of the effective threshold, lowering it to 2.5 fC for a complete board.

For the 1 × 1 m² prototype, a new set of readout electronics have been designed: the test board functions have been split between so-called ASU (Active Sensor Unit) boards holding 24 HaRDROC ASICs each, which can be coupled together at their ends, and a readout and controller card named “DIF” (for Detector InterFace). A 1 × 1 m² chamber is readout by 6 ASU connected to 3 DIF’s, for a total of 9216 channels. The acquisition is performed through USB by a software developed in the XDAQ framework.

3. Test beam setup
Up to 4 test boards were equipped with GRPC, of various types, and were used in test beam near the PS and SPS CERN facilities. They were installed perpendicularly to the beam in a structure eventually allowing for the installation of 2 cm-thick stainless steel radiators, to build a mini calorimeter, associated with a set of scintillators for triggering purposes.

Two campaigns of tests were performed in 2008 and 2009 each using low (3–12 GeV) and high (10–150 GeV) energy pions. The results presented here are restricted to the mip-like data sample (no absorbers used).

3.1. Acquisition modes
The on-board FPGA’s were programmed to manage two acquisition modes relying on the auto-trigger feature of the HaRDROC’s:

- **a train mode** (“ILC like”), where the readout is started on the start-of-spill signal and stopped on the end-of-spill signal or when one of the ASIC is full;
- **a triggered mode** used for cosmic rays and test beam data taking, where the acquisition is stopped on an external trigger. When the memory one of the ASIC’s is full, a busy signal is emitted, the entire board reset and the acquisition resumed.

In both cases when the acquisition is stopped, a train of up-to 127 events is readout.

Using the coincidence of plastic scintillator plates readout by photo-multipliers as an external trigger a total of about 1,130 million triggered events were collected, at an average DAQ rate of ~ 20 Hz.

Figure 2. Time-to-trigger distribution; the events associated with the trigger are in the last 200 ns (right peak), in-spill events in the last 20 ms (detail in insert) while the previous spill is visible at -2000 ms. All events in between are considered as being noise.
3.2. Timing
At PS, 2 spills of 400 ms were received, at 2 second interval, every 48 s during the day (every 33 s during the night).

The synchronisation between the boards was ensured by a 40 MHz counter recording the time difference for each board between the last internal trigger and the external trigger. This allows to resynchronise of each board w.r.t. the trigger signal and to reconstruct the history of all boards back to the last memory reset. In most cases (low noise and particle density), the last event in memory of the ASIC in beam corresponds to the signal of the triggering particle.

By studying the correlation in time between hits of different cards, it has been observed that their clock’s dispersion is small enough to allow a tight cut of 300 ns (w.r.t. their 200 ns period) to cluster hits in individual events due to a particle or noise.

This time reconstruction allows the use of events from memory which were not triggered by the scintillators in the beam. Such a time reconstruction is shown in figure 2. In particular the noise pattern can be separated from in-spill events, dominated by particles.

4. Small chambers results
4.1. Efficiency & multiplicity studies
Using the 3 other chambers as a crude tracking device one can determine the position of the particle in the 4th one and calculate the efficiency and multiplicity locally. The multiplicity $\mu$ is defined as the number of fired cells within 3 cm-radius around the impact when the chamber has responded ($\mu \geq 1$)

For the following studies one of the two following selection was applied :

- using only the last event in memory (triggering one), with $t > 400$ ns
- using the complete train statistics, in which case only the hits in time ($|\Delta t| < 300$ ns and after the most recent board reset ($t >$ time of first event in every chamber) were used.

A high voltage scan was performed with a threshold set to 165 fC with the different small chambers based on float glass (2 identical “Graphite”, 1 “Licron” and 1 “Statguard”).

Using the triggered event sample it was found that a maximum efficiency of about 98% was reached for all chambers but for the Licron one saturating at $\sim 90\%$. As can be seen on figure 4 the efficiency and multiplicity were found to rise faster for the graphite covered chambers w.r.t. the Licron and Statguard ones. An efficiency plateau is reached for all chambers around 7.2 kV, while the multiplicity rises continuously with the HV.

A working point of 7.4 kV (for a threshold of 165 fC) was chosen as standard for the following studies, being seen as a good compromise between high efficiency and low multiplicity. At this point the multiplicities are of 1.3 for the “Licron” chamber and $\sim 1.6$ for the “Statguard” and “Graphite” ones.

Figure 3. Efficiency and multiplicity vs HV for the 4 small float glass chambers.
Threshold scan: The efficiencies and multiplicities were measured as the threshold applied was varied around 165 fC, and found to behave as expected, as the inverse of the HV; the efficiency was found to be 80% at 7.4 kV for a threshold of 1.1 pC. This will be used to model the response of the chambers.

Chamber uniformity: The response ($\epsilon, \mu$) of 4 similar small graphite chambers produced by the IHEP at Protvino were studied and found to have identical behaviour with a spread of the efficiency of 95 ± 3% and multiplicity of 1.6 ± 0.4.

Using the train sample reconstruction individual response of the 1x1 cm$^2$ cells could be studied with a good statistics. A global efficiency spread, including the statistics error for about 25k events, of 3% was observed inside single chambers and between different chambers. The multiplicity spread in a chamber is of $\sim$ 0.2. The main sources of variation (lower $\epsilon$ and $\mu$) are due to the fishing lines and the chamber edges as can clearly be seen on figure 4. Some inefficiencies were also clearly observed at the centre of the beam spot for high rates run (19 kHz/cm$^2$).

In the future prototypes, the fishing lines will be replaced by ceramic balls, reducing the size of the affected region by a factor of 100.

Angular response & stability: No observable difference was seen while shooting with an angle up to 60°. This will ease the reconstruction code for large detectors.

The global behaviour was found to be constant over the time of the running (10 days), with a number of dead or inefficient cells limited to 1%.

4.2. Noise studies
Observing only out-of-spill events and out-of-trigger cosmic data, one has access to the noise distribution. The noise rate was studied and found to be higher near the special regions (especially fishing lines and to a lesser extend borders), with rates typically of 20 Hz/cm$^2$ for our standard threshold (165 fC) going down to 10 times less when the threshold is raised at 750 fC.

In the bulk, the noise rate was found to be of 0.1 Hz/cm$^2$, with no dependence on the applied threshold (between 165 and 750 fC). It evolves slowly with HV with a slope roughly estimated $\sim$ 0.3 Hz/cm$^2$/kV around our working point.

4.3. Semi-conductive GRPC’s
Two small chambers provided by Tsinghua University and based on semi-conductive glass ($10^{10}$ Ω/cm against $10^{13}$ Ω/cm for classical float glass) have been tested at high rates. A “thin” version features glass thickness of 0.83 mm on the anode side and 1.1 mm on the cathode one, coated with Statguard. A “thick” version uses 1.1 mm glass on both sides, with a Licron coating.

As can be seen on figure 5 an efficiency curve similar to the standard chambers could be achieved, with efficiency reaching a plateau at 90% above 7.4 kV, but here with rates above 10 to 30 kHz/cm$^2$, when the standard chambers start to become inefficient above 10–100 Hz.
5. First results on a 1 m² prototype

The square meter prototype was put in beam at the SPS. The acquisition worked as expected and was able to read the 9216 channels; the beam spot was observed and efficiencies of up to 93% have been obtained. But the setup rapidly suffered from faulty mechanics on the HV connection and these results will have to be confirmed.

On a cosmic test bench, using the mini-DHCAL as a tracker device, cosmic tracks were collected. For analysis purpose, the surface was divided as a checker of 9 regions of $33 \times 33 \text{cm}^2$. One of the regions failed during this test. Between the 8 other working regions a good uniformity of response was observed with results similar to the ones of the small chambers (working HV $\sim 7.4 \text{kV}$, $\epsilon \sim 95\%$ and $\mu \sim 1.6$).

Conclusions & perspectives

A Semi-Digital Gas Hadronic Calorimeter with embedded readout is a very promising candidate for future linear collider experiments. The main critical parameters have been checked at beam tests on float glass small chambers prototypes: in response to single minimum ionising particle a high efficiency ($\epsilon \sim 95\%$), low multiplicity ($\mu \sim 1.6$), no angular dependency, spatial and detector uniformity ($\sigma_\epsilon \lesssim 2\%$, $\sigma_\mu \lesssim 3\%$ over 256 cells of 1 cm$^2$) and low noise have been measured. Some prototypes using semi-conductive glass showed some promising performances for high rates ($\gtrsim 10 \text{kHz/cm}^2$). The first measures made on a square meter sensor similar to the one foreseen for a technological prototype of 1 m$^2$ (including 40 of these) were found to be similarly satisfying. The full prototype is expected to be completed in 2010.

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