Development of a Gas Electron Multiplier -based Digital Hadron Calorimeter

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Abstract. We describe the development of large-area (1m x1m), very thin, and high sensitivity gas detector based on gas electron multiplier (GEM) technology as a sensitive medium for sampling calorimeters for a use in future collider experiments.

1. Introduction

Experiments at future high energy colliders aim for high precision measurements of physics processes and exploration of new physics areas – electroweak symmetry breaking, the Higgs boson and its properties, the origin of mass, and searches for super-symmetry, extra space-time dimensions, and the emergence of unexpected new particles and forces. Much of this ambitious physics program requires high-precision measurements of jet energies and jet-jet invariant masses. This paper reports on the development of large area Gas Electron Multiplier (GEM) [1] technology as an important option for implementing calorimetry for future collider experiments.

A promising new approach to the calorimetric measurement of jet energies, the Particle Flow Algorithm (PFA) approach, is based on the observation that over 60% of the particles in jets are charged particles; therefore their momenta can be measured with high precision in the detector's tracking system. Recently, the PFA approach to jet-energy measurement has received considerable attention; it has been the subject of development by CMS [2] at the LHC and two of the major ILC detector design groups [3,4] and for CLIC[5].

Using small calorimeter cells, typically a few cm², makes it possible to track charged particles in the calorimeter and associate their energy deposits with the corresponding tracks from the tracking system. After removal of this charged-particle associated energy from the calorimeter information, the remaining energy is measured using the residual hits in the calorimeter, namely those without associated incoming charged particle tracks. Our studies have shown that there is an approximately linear relationship between the number of digital hits, associated with a track producing a calorimeter cluster, and the cluster's energy [6] as shown in Fig.1. Using digital hadron calorimetry, in which a cell is either on or off, but no
The approximately linear relation between digital hits and energy for a simulated GEM-based digital hadron calorimeter.

Analog signal measurement is made, along with this new PFA approach, an overall hadronic (jet) energy resolution of about 3 – 4% for a range of jet energies up to 500 GeV should be achievable. We note that for 100 GeV this corresponds to \(3\%\sqrt{E}\).

Our proposed digital hadron calorimeter comprises a stack of steel absorbers, of sufficient thickness to contain hadronic showers, interlaced with active gaseous sampling elements. A primary concern is to keep the active layer thickness small to minimize lateral spread of the showers and as it is repeated typically 40 times through the limited depth of the calorimeter stack which could be located inside a high-cost superconducting magnetic coil in lepton collider experiments. In order to take full advantage of the PFA approach, it is of critical importance to minimize contributions to the energy resolution due to confusion in track-energy cluster matching. Accomplishing this requires a calorimeter that can provide excellent matching between energy clusters and tracks whose momenta are measured in the tracking detector. This means a small cell size and fine readout granularity for which GEM offers a promising solution. The basic layout of a GEM-based digital hadron calorimeter is shown in Fig. 2, which also shows details of our double-GEM structure.

![Figure 2](left) Principle of GEM DHCAL implementation using GEM layers, (right) Details of double-GEM structure used in each DHCAL layer
2. Prototype Development
We have built and tested a series of GEM chamber prototypes, using 30cm x 30cm foils first from 3M Corporation, and later from CERN. Figure 3 shows a prototype chamber with an 8 x 8 array of 1 cm$^2$ anode pads. We use an 80/20 Argon/CO$_2$ gas mixture, which gives a gain of up to 11,000 from the double foil arrangement. Figure 3 also shows the results of exposing the chamber to an $^{55}$Fe source. The characteristic double-peak spectrum can clearly be seen for each cell.

![Figure 3. (left) GEM-DHCAL prototype chamber with 8x8 anode pad array, (right) $^{55}$Fe spectrum in each channel – red circle indicates source position.](image)

For the readout of the pad signals we have used three approaches. In early tests, and to establish a baseline for each new chamber, we have used a single channel analog chip. For multi-pad readout we have used two chips, the analog KPiX chip [7] from SLAC, and the digital. DCAL chip [8] from ANL. One anode pad is connected to one channel on a chip. The KPiX chip has a four-deep pipeline, on-board DAC charge injection calibration, and a Wilkinson 13-bit ADC for each channel. The digitized signals are readout via an FPGA then sent to a PC via a USB connection. The DCAL chip outputs a digital result by comparing the signal from a pad with a pre-downloaded threshold. The collected digital results are read out via a data concentrator to a VME system. Since a final digital hadron calorimeter system would have about 50 million pixels, there is a critical need to have a high-density readout scheme.

In the process of constructing prototype chambers using the 30cm x 30cm foils from CERN GDD, we encountered gains smaller than anticipated. We have learned that the standard foil production technique at present focuses more on the stability of the detector than higher gains. Since for DHCAL, it is necessary to maintain the detector as thin as possible, we use a double-GEM layer configuration instead of triple-GEMs. This requires the gains from each of the GEM layer to be as high as possible without damaging the foil surfaces from frequent discharges. To remedy this issue, we requested CERN to produce GEM foils with higher gain and we measured the gains from detectors with the two different sets of GEM foils. Since the two sets of GEM foils show dramatic differences in gains, we decided to construct 30cm x 30cm prototype detectors for beam test using the higher gain GEM foils.
3. Test beam results
We constructed one \(30\text{cm} \times 30\text{cm}\) chamber with the 13-bit KPiX9 readout board with 64 active channels in the center and three chambers with DCAL boards that have a center \(16\text{cm} \times 16\text{cm}\) active area. We exposed these four chambers to particle beams in August 2011 at the Fermilab Beam Test Facility (FTBF)[9]. We took a total of 7 million events with 32 GeV muons and pions, as well as 120 GeV protons. The data were taken to measure chamber responses, gains as a function of high voltage across each GEM foil, position dependence of the response and threshold dependences of efficiencies. In addition, we took a 32 GeV pion shower run with 8-inch steel bricks causing the pions to shower in front of the detector array.

Figure 4 (left) shows a photograph of our test beam set up with the stack of 8-inch steel bricks in front of the detector array that causes pion showers. Beam was incident from the left hand-side of the photo.

![Figure 4. Four GEM chamber setup at Fermilab Test Beam Facility.](image)

Figure 4 (right) shows the distributions of the numbers of hits from the single pions (black) and the pion shower (red) above 5fC measured in the 13 bit KPiX chamber. One can clearly see the dramatic difference between these two sets of data. This indicates that the chambers and the electronics can handle multiple simultaneous hits. A similar trend is seen for the three DCAL chambers as well, depicting progressively broadened hit patterns in the chambers as the shower propagates downstream.

![Figure 5. (left) Measured GEM chamber efficiency above threshold for various high voltages. (right) Chamber efficiency vs. number of cells hit.](image)
We measure a chamber gain of about 11,000 at an operating voltage of 390V across each GEM foil, consistent with other previous results. Figure 5 (left) shows the chamber efficiency as a function of threshold for three different high voltages across the chamber. The preliminary chamber efficiency is measured to be 98% with 2fC threshold.

Figure 5. (right) shows how the number of hit cells for one incident charged muon correlates with chamber efficiency. The figure indicates that for an efficiency of ~95% there is on average only a 50% chance of an extra hit. This would be a good operating point for a calorimeter system designed for particle flow.

4. Development of Large Area Chambers

The next phase in our work is the development, characterization and construction of full scale 1m$^2$ GEM chambers for DHCAL. We are developing the mechanical structure, the electronic readout board schemes and the schemes for integrating the three unit chambers (33cm $\times$ 100cm) into one 1m $\times$ 1m plane. We plan to construct two of these 33cm $\times$ 100cm unit chambers in the next year. The team has been working with the CERN GDD workshop [10] in developing 33cm $\times$ 100cm GEM foils. The foils have been made using a new single-sided-etching approach, which eliminates some of the manufacturing problems associated with side-to-side registration in the standard double-sided-etching process. The first set of five foils has been produced and delivered to UTA. Testing and qualification of these foils were carried out in a systematic study by UTA students. In order to test and qualify these foils, the resistance of each of the 31 independent HV strips on each foil was measured using the Keithley6145 electrometer. The instrument measures the resistance by applying constant amount of current 1nA and measure the voltage difference across the top and bottom of the foil. The saturation voltage corresponds to a resistance of 260GΩ. A foil is considered qualified if all strips have the saturation voltage, indicating the resistance of the strips greater than 260GΩ.

We have completed the design of the first 33cm $\times$ 100cm chamber whose schematic diagram is shown in Fig. 6 (left). In order to avoid thick side walls for the chamber resulting from tensioning the large foils, we will use a 2mm steel strong-back on which to mount the chamber. In a final calorimeter configuration, this would be part of the absorber structure between two active layers. The required separation of the cathode, foils and anode layers is achieved by the use of thin spacers, also made for us by the CERN GDD Workshop.

Fig. 6 (right) shows a 33cm x 100m chamber under construction at UTA. Once we have assembled, tested, and successfully operated a 33cm $\times$ 100cm chamber, we will proceed to construct and test a full 1m $\times$ 1m plane. A schematic view of such a plane is also shown in Fig. 6 (right).
We will build 6 additional 33cm \times 100cm unit chambers for two 1m \times 1m planes and characterize using long-term cosmic rays tests. We will then integrate three 33cm \times 100cm chambers with DCAL chip based anode boards for assembly of each final 1m \times 1m DHCAL sensitive gap plane. As funding allows, we will construct nine more 33cm \times 100cm unit chambers for three additional 1m \times 1m chamber planes using DCAL readout boards. In the long term these chambers will allow us to construct a total of fifteen 33cm \times 100cm unit chambers for five DCAL 1m \times 1m chamber planes. These five planes will then be inserted into the existing CALICE calorimeter stack and run together with the Si/W ECAL and 35 RPC planes in the HCAL.

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