# Development of GEM Based Digital Hadron Calorimeter


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## 1. Introduction

The International Linear Collider (ILC) [1] is a precision machine with high physics potential thus ILC must be accompanied by detectors capable of disentangling and deciphering complex signatures that are densely packed in both space and time. Excellent energy and angular resolution of parton-initiated "jets" are essential to precise measurements of cross sections and invariant masses of resonance states. In particular, accurate measurements of jet energy and missing energy are critical for discovery and characterization of the Higgs bosons and supersymmetric particles.

The Particle Flow Algorithm (PFA) [2] initially developed by the ALEPH experiment [3] at LEP is considered to be a solution to improve jet energy resolution. PFA exploits the relatively superior resolution of tracking systems, by replacing calorimeter cluster energies with the momenta of the associated charged tracks, thereby improving jet energy resolution. PFA requires fine calorimeter segmentation and a large tracking volume to precisely associate energy clusters with the track and to remove only the energy corresponding to the track. Fine segmentation requires a large number of readout channel, consequently instrumentation of the next generation of detectors capable of exploiting PFA using the current analog calorimeter technology may be prohibitively costly.

Digital calorimetry [4] measures the energy deposit by simply counting cells above the threshold. Such counting requires only binary information with little dynamic range, thus reducing costs for readout electronics relative to an analog calorimeter of the same granularity. Over the past several years the University of Texas at Arlington (UTA) team has been developing a digital hadronic calorimeter (DHCAL) using a Gas Electron Multiplier (GEM) [5] as the sensitive gap detector. GEM can provide flexible configurations which allow small anode pads for high granularity. It is robust and fast with only a few ns rise time and has a short recovery time which allows higher rate capability. It operates at a relatively low voltage across the amplification layer, uses simple gas (ArCO2) which prevents the detector from long term issues and is stable.

In this report, we present the recent results of the GEM based DHCAL R&D activities including some preliminary results of beam tests at Fermilab's Meson Test Beam Facility (MTBF) and the plans for the near and mid-term future.

## 2. GEM-Based Digital Hadron Calorimetry Prototypes

Our development effort using GEM for a DHCAL is essential for PFA approach to achieve the required jet energy and jet-jet mass resolution. The ionization signal from charged tracks passing through the drift section of the active layer is amplified using a double GEM layer

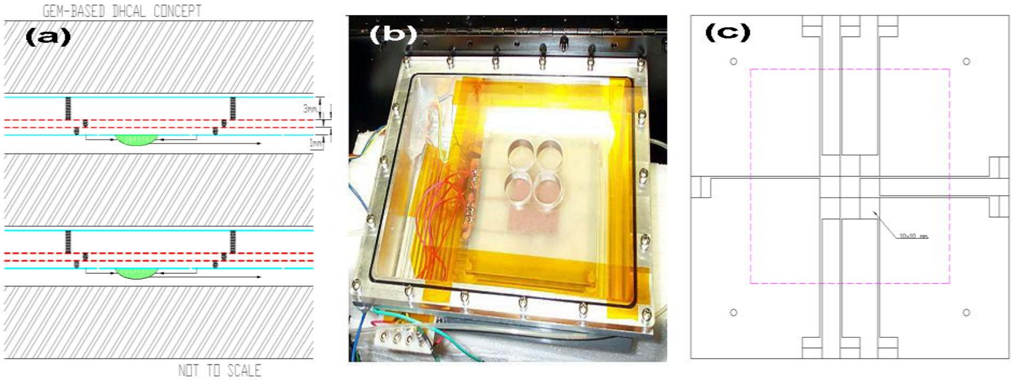



**Figure 1. (a) GEM DHCAL concept diagram (b) UTA GEM prototype chamber constructed with $10\,\text{cm}\times10\,\text{cm}$ CERN GDD GEM foils (c) Prototype readout anode pad with nine $1\,\text{cm}\times1\,\text{cm}$ cells**

structure. The amplified charge is collected at the anode layer with $1\text{cm}\times1\text{cm}$ pads at zero potential.

The potential differences, required to guide the ionization, are produced by a resistor network, with successive connections to the cathode, both sides of each GEM foil, and the anode layer. The pad signal is amplified, discriminated, and a digital output produced. As pointed out above, GEM design allows a high degree of flexibility with, for instance, possibilities for microstrips for precision tracking layer(s), variable pad sizes, and optional ganging of pads for finer granularity future readout if allowed by cost considerations. Figure 1.(a) depicts how the GEM approach can be incorporated into a DHCAL scheme.

Initial studies were conducted on signal characteristics and gain from a small prototype GEM detector shown in Fig. 1.(b). The signals from the chamber are read out using the QPA02 chip developed by Fermilab for Silicon Strip Detectors. The gain of the chamber was determined to be of the order 3,500, consistent with measurements done by the CERN GDD group. The MIP efficiency was measured to be 94.6% for a 40 mV threshold, which agrees with a simulation of chamber performance. The corresponding hit multiplicity for the same threshold was measured to be 1.27, which will be beneficial for track following and cluster definition in a final calorimeter system. A gas mixture of 80% Ar/20% $CO_2$ has been shown to work well and give an increase in gain of a factor of 3 over the 70% Ar/30% $CO_2$ mixture. A minimum MIP signal size of 10 fC and an average size of 50 fC were observed from the use of this new mixture. The prototype system has proved very stable in operation over many months, even after deliberate disassembly and rebuilding, returning always to the same measured characteristics. We also investigated cross talk properties using nine $1\,\text{cm}\times1\,\text{cm}$ cell anode pad layout shown in Fig.1(c). We also used collimated gamma rays from a $^{137}$Cs source to study signal sharing between adjacent pads.

# 3. Development and Beam Tests of $30\text{cm}\times30\text{cm}$ Chambers

As the first step for the full-size (1m×1m) test beam chambers, we have developed a $30\text{cm}\times30\text{cm}$ GEM foils as shown in Fig. 2.(a) together with Microinterconnect Systems

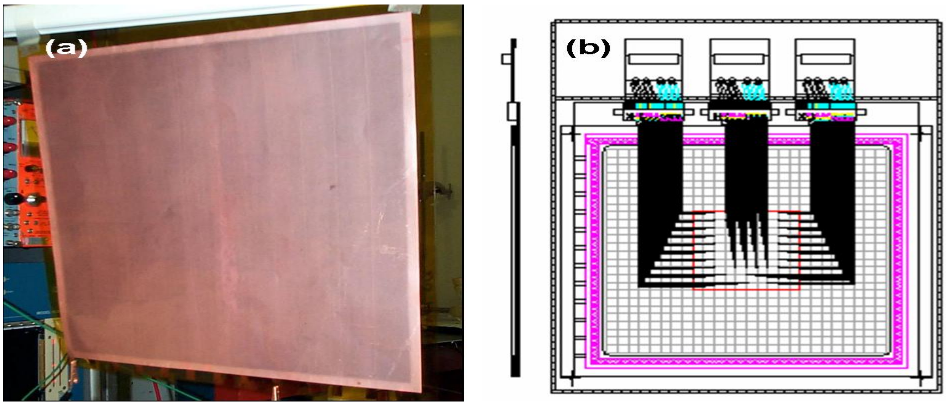


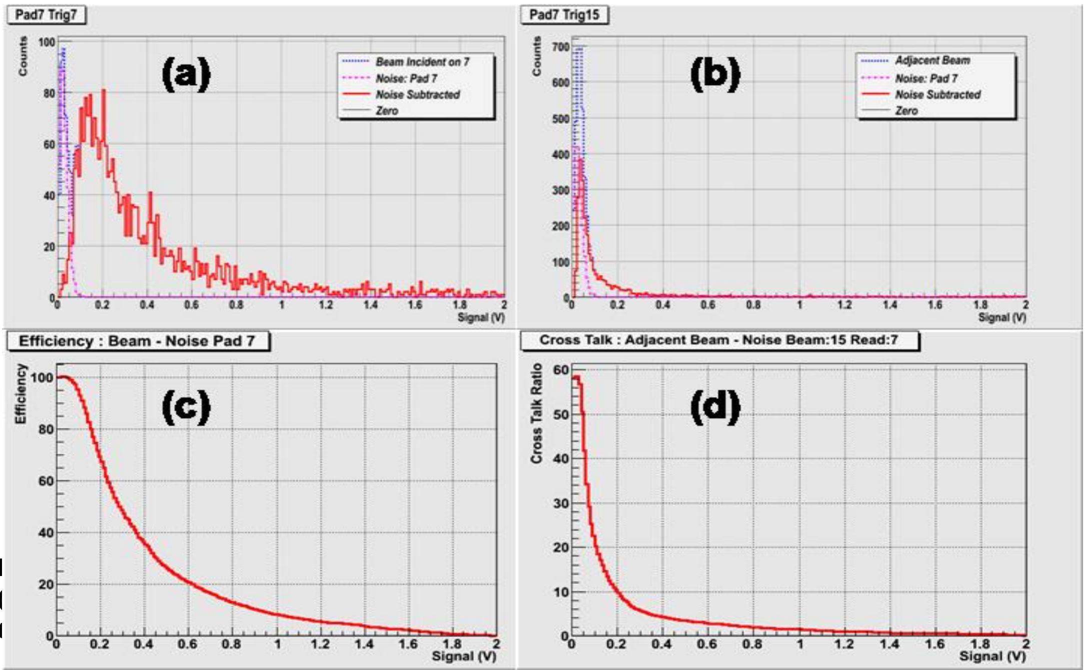

**Figure 2. (a) A photo of one of the $30 \times 30\,\mathrm{cm}^2$ 3M GEM Foils (b) A schematic diagram of a 96 channel anode board with three 32 channel Fermilab QPA02 front end electronics**

Division of 3M Corporation [6]. The foil is divided into 12 independent HV strips for operational safety which we had to disconnect a few during beam test experiments. For mechanical assembly, we have developed tools to handle large area foils, maintaining flatness of the foils, and the detector walls that provide gas and HV feed through. A modification of this foil design will allow sections of 1m x 30cm foils for the unit chamber. We constructed several prototype chambers using these foils and the readout boards shown in Fig.2.(b) and expose them into various beams. These chambers were read out using the 32-channel QPA02 chip based Fermilab preamp cards.

In order to test the chambers properly with sufficient statistics, they need to be exposed to particle beams. We conducted three beam tests to measure rate capability of the chamber, its MIP characteristics, cross talk between the channels and occupancy from this exercise. The output signals from the amplifier cards will be sent to discriminator boards which contain discriminator chips, multiplexer stages, and data output interface. The output from the discriminator boards were read out by a PCI based ADLink ADC controlled by LabView software.

The first beam exposure of our $30\,\mathrm{cm} \times 30\,\mathrm{cm}$ prototype chamber took place in May 2006, at the high intensity, low energy (10 MeV) electron beam at the Korean Atomic Energy Agency (KAERI). This beam exposure was a joint effort between UTA and the Radiation Detector Development (RDD) Group at Changwon National University (CNU), Changwon, Korea. Since the beam consists of 30 ps pulses of $10^{10}$ electrons every 43 μs in 5 cm radius, the detector and the electronics measured responses to $10^9$ electrons per pad. While the electronics was saturated, the chamber was able to see the beam clearly and provided a good measure of the time structure of the beam. As a test, we directly exposed a broken GEM foil to the beam. In both the chamber and the broken GEM foil, we did not see any physical damages. In addition, while the signal shapes were distorted by the hit from $10^9$ electrons per pad, the chamber responded well to such a large signal, giving us confidence that the chamber will function in the ILC environment without damage.

In order to continue testing GEM-based DHCAL for in-beam characterization, we performed additional beam tests at Fermilab's Meson Test Beam Facility (MTBF). We tested




a single multi-channel chamber using the 100 channel readout system for one week in March 2007 for joint run with CNU as a secondary user behind a straw channel detector group and one week in April, 2007, as the primary user. Most the useful data taking was done using 120 GeV proton beams from the Main Injector. Labview based online analysis software complimented the DAQ software and allowed us to monitor the data as they got accumulated. Since the DAQ card required sufficiently long signal for an efficient sampling, we developed a pulse shaper to stretch the signal to a suitable level for the ADLink DAQ card to sample. We also used a commercial shaper for a verification purposes.

The trigger was formed of coincidences of three $1\,\mathrm{cm}\times 1\,\mathrm{cm}$ and two $19\,\mathrm{cm}\times 19\,\mathrm{cm}$ counters to constrain the beam to smaller than $1\,\mathrm{cm}\times 1\,\mathrm{cm}$ region, which is the size of a readout pad. The two $19\,\mathrm{cm}\times 19\,\mathrm{cm}$ counters enveloped the GEM prototype chamber to ensure the beam passage through the active area of the detector. In addition to the beam trigger, we employed two additional triggers: chamber self trigger with the signal above 30mV, utilizing the negative output from Fermilab QPA02 preamplifier, and the coincidence between the five counters and a pad signal above 30mV to constrain the beam on a particular target pad.

Using the data collected in the MTBF beam tests, we were able to determine relative efficiency and fractional cross talk ratio. In order to verify the proper functionality of the chamber, we took data using a high intensity $Sr^{90}$ radioactive beta source. Figure 3.(a) shows the signal without noise subtraction (blue), noise (purple) and noise subtracted signal (red) when 120GeV proton beam is incident to the target pad. Noise subtracted signal distribution demonstrates Landau shape as expected. We, however, observed that the width of the distribution from proton beams is much wider than the source.

Figure 3.(c) shows the relative efficiency measured on this pad as a function of threshold, which demonstrates that at the efficiency about 94% at 40mV. It, however, should be noted that a sizable number of events have more than one proton entering the detector within the 200ns gate. This is the apparent reason why we observed differences in the widths in noise subtracted signal distributions. An initial estimate of the multiple proton events shows about 20% multiple proton event contamination. A more detailed analysis using the differences between the data obtained from the $Sr^{90}$ source and the proton beams is in progress.

In order to measure the cross talk rate, we read out the pad immediately next to the pad with the trigger. Figure3.b shows the pulse height distributions of the pad number 7 when beam is incident on the immediate neighboring pad. Blue dotted lines represent the signal before noise subtraction, the purple lines represent noise, and the red line is the noise subtracted signal. The difference between the two cases is apparent from the two figures. From these, we can extract the fractional cross talk rate on a pad, as shown in Fig.3.d. From these studies, while the probability of the cross talk is small for both the pads, it should be emphasized that given the size of the trigger paddle this distribution includes charge sharing between the neighboring pads and the multiple proton events. As in the cases before, a more systematic analysis is in progress to take into account these different effects.

# 4. Future Plans

We plan to conduct a beam test using both the digital readout chip (DCAL) developed jointly by ANL and FNAL and the kPiX analog readout chip developed by SLAC in fall 2007. The prerequisite for this test is the verification of the functionality of the chamber with these readout chips in bench tests. We are working with the ANL RPC team to establish a DCAL chip test station at UTA for more efficient chamber construction and testing.

The next phase is the beam test of the full scale $1m^3$ GEM DHCAL prototype together with an electromagnetic calorimeter. We plan to construct a total of 50 or so (40+10 spares) chamber layers using $1m\times30cm$ GEM foils produced by 3M. Three of these unit chambers will make up one sensitive layer of size $1m\times1m$. This test will be performed at the MTBF in late 2008 or 2009. The goal of this test is to measure the responses and energy resolution of a GEM-based DHCAL. This result should be compared to that of a DHCAL using RPCs and other analog HCALs. This full scale prototype will be tested jointly with CALICE Si/W or Scintillator/W ECAL and a tail catcher (TCMT), using the CALICE mechanical support structure which was used in this year's CERN beam test. This phase, however, depends heavily on the availability of funds.

# 5. Possible Alternatives to Standard Thin GEM Foils

We have been considering an alternative to the standard GEM foil technology. Recent work [7] has shown that a so-called "thick-GEM" (TGEM) can, in a single layer achieve multiplication levels typical of at least a double-GEM device. A TGEM is a printed circuit board, clad with copper on both sides through which holes have been drilled. A typical configuration might be a 0.4 mm thick board with 0.3 mm diameter holes spaced 1 mm apart. Since in our application we use relatively large pads compared say to a microstrip tracker the sparser array of holes should not be an issue. With the detector costs scaling as +$12M/mm increase of the superconducting coil diameter, this could be a significant cost saving.

We have obtained a few TGEM samples from the Weizmann Institute and are in the process of constructing a prototype for feasibility study. In addition, the recent development of resistive-electrode TGEM (RETGEM) [8] will also be investigated as an alternative solution for the overall ILC detector.

**6.0 Conclusions**

Gas electron multiplier technology demonstrates exceptional possibilities of use, from time projection chambers to digital hadron calorimeter to muon tracking chambers. The development of large area GEM foils enables a wide variety of use in various detectors. The research and development work in progress of using GEM is at the stage to measure the performance of the conceptual GEM-based DHCAL. Following the three single chamber beam tests, we plan to perform additional tests using multi-channel ASIC chips. We also plan to construct a 40 layer 1m$^3$ calorimeter prototype to measure the calorimetric performance. TGEM foil developed by Weizmann institute and the RETGEM are of great interest due to their potential for cost savings in large area production.

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