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Application of Large Scale GEM for Digital Hadron Calorimetry

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Abstract

The detectors proposed for future e+e- colliders (ILC and CLIC) demand a high level of precision in the measurement of jet energies. Various technologies have been proposed for the active layers of the digital hadron calorimetry to be used in conjunction with the Particle Flow Algorithm (PFA) approach. The High Energy Physics group of the University of Texas at Arlington has been developing Gas Electron Multiplier (GEM) detectors for use as the calorimeter active gap detector. To understand this application of GEMs, two kinds of prototype GEM detectors have been tested. One has 30x30 cm² active area double GEM structure with a 3 mm drift gap, a 1 mm transfer gap and a 1 mm induction gap. The other one has two 2x2 cm² GEM foils in the amplifier stage with a 5 mm drift gap, a 2 mm transfer gap and a 1 mm induction gap. We will summarize the results of tests of these prototypes, using cosmic rays and sources, in terms of their applicability to a digital hadron calorimeter system. We will discuss plans for the construction of 1m² layers of GEM digital hadron calorimetry to be used as part of a 1m³ stack to be used in a major test beam study of hadronic showers.

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1. INTRODUCTION

THE precision measurements of physics topics at future particle accelerators such as the International Linear Collider (ILC) [1] or CLIC [2] demand unprecedented energy resolution of jets to distinguish various resonances that result in multiple jets in the final state. Particle Flow Algorithm (PFA) [3] is a solution that could be used to accomplish such a superb jet energy resolution. In order to take full advantage of PFA, it is of critical importance to minimize the energy resolution caused by the confusion

terms resulting from incorrect association of tracks and energy clusters. 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 small cell size and high readout granularity. Given the cost of readout electronics, reading out such a high granularity in multiple-bits could make such a calorimeter prohibitively expensive. One-bit readout per cell, however, could reduce the cost per readout channel dramatically and thus provide a possibility of greatly reducing the overall DAQ system costs. Gas Electron Multiplier (GEM) [4, 5] is a technology that was invented in the late 90's at CERN and has been used in tracking detectors. Thus, GEM can be used as a sensitive medium in a high granularity calorimeter.

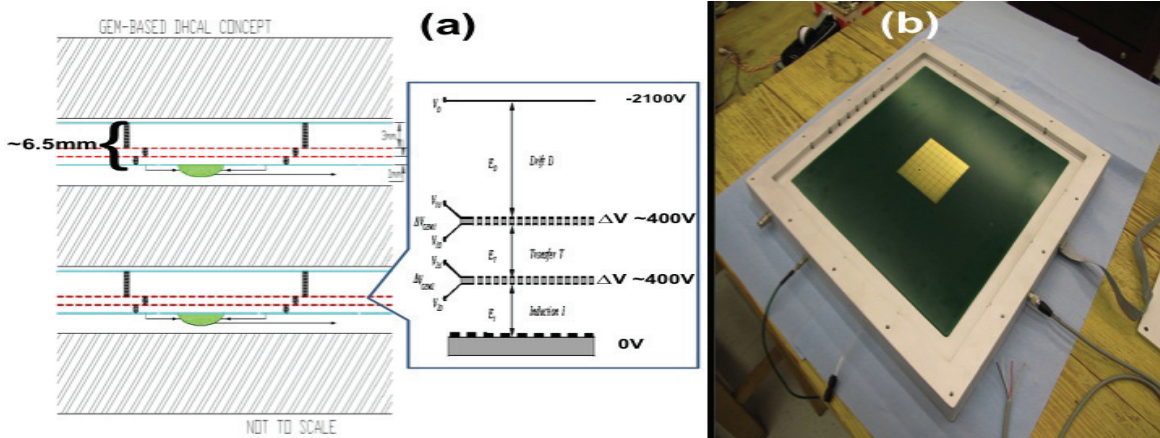
Over the past several years the University of Texas at Arlington (UTA) team and collaborators from other institutions listed have been developing a digital hadronic calorimeter (DHCAL) [6 – 8] using GEM as the sensitive gap detector technology. GEM can provide flexible configurations which allow small anode pads for high granularity. It is robust and fast with only a few nano-second rise time and has a short recovery time which allows higher rate capability than other detectors, such as Resistive Plate Chambers (RPC) [9, 10]. GEM operates at a relatively low voltage across the amplification layer, can provide high gain using simple gas (ArCO_2) which protects the detector from long term issues, and is stable.

The ionization signal from charged tracks passing through the drift section of the active layer is amplified using a double GEM layer structure. The amplified charge is collected at the anode layer with $1\text{cm} \times 1\text{cm}$ pads at zero volts. The potential difference, required to guide the ionization, is 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. 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 double GEM approach can be incorporated into a DHCAL scheme with the inset showing the detailed structure of the sensitive gap.

2. The Initial Study with $10\text{cm} \times 10\text{cm}$ and $30\text{cm} \times 30\text{cm}$ Prototype Chambers

The initial studies were conducted on signal characteristics and gain from a prototype GEM detector using $10\text{cm} \times 10\text{cm}$ GEM foils. The signal from the chamber was 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%

Figure 1. (a) GEM DHCAL concept diagram with a double GEM layers as shown in the inset to keep the sensitive gap size as small as possible (b) UTA GEM prototype chamber constructed with $30\text{cm} \times 30\text{cm}$ CERN GDD GEM with 64 channel KPiX readout board



CO₂ has been shown to work well and give an increase in gain of a factor of 3 over the 70% Ar/30% CO₂ 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 investigated cross talk properties using nine 1 cm×1 cm cell anode pad layout. We also used collimated gamma rays from a ¹³⁷Cs source to study signal sharing between adjacent pads. These chambers were read out using the 32-channel QPA02 chip based Fermilab preamp cards. 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 were sent to discriminator boards which contained 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.

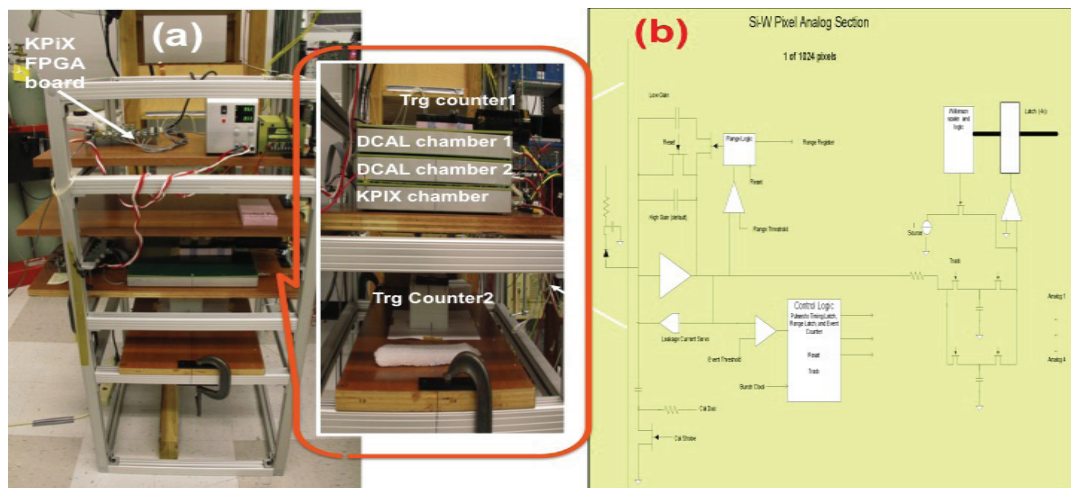
The first beam exposure of our 30 cm×30 cm prototype chamber took place in May 2006 at a high flux electron beam which consists of 30 ps pulses of 10¹⁰ electrons every 43 μs in 5 cm radius. The detector and the electronics measured responses to 10⁹ electrons per pad. While the electronics was saturated, 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 damage. In addition, while the signal shapes were distorted by the impact of 10⁹ 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.

Additional beam tests were conducted at Fermilab's Meson Test Beam Facility (MTBF) [11] in April 2007. Most the useful data taking was carried out 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. These results were reported in Ref.[12].

3. Development and Characterization of 30 cm×30 cm Prototype Chambers using 13-bit KPix Chip

As the continuation of the chamber characterization process and as the first step for the full-size (1 m×1 m) test beam chambers, we have been developing a 30 cm×30 cm GEM prototype chambers read out with the 64 channel 13bit KPix[13] chip originally developed for the SiD silicon-tungsten (Si/W) electromagnetic calorimeter (ECAL) [14,15]. The chip has been modified to include a switchable gain to accommodate small signals from GEM chamber. Figure 1.(b) shows a photo of the readout anode board

Figure 2. (a) Cosmic ray test stand with KPix DAQ electronics. Inset shows three 30 cm×30 cm prototype chambers of which one is read out with the 13bit KPix chip while the other two with 1bit DCAL chip. (b) A schematic diagram of one of the 64 channels of the 13bit KPix chip.



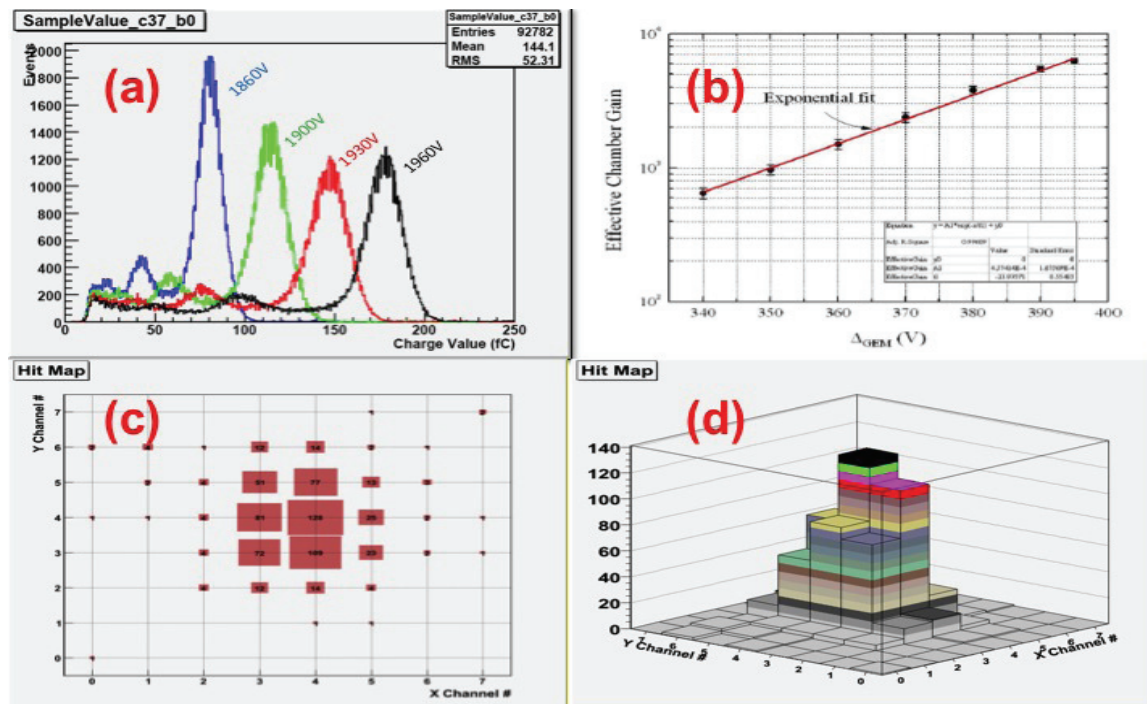
integrated into a prototype chamber.

For mechanical assembly, we have developed G10 based grid spacers with the grid size 8cm×8cm sufficient for keeping the foils flat and maintain efficient uniform gas flow throughout the entire detector gas volume. The detector enclosure was constructed with a one-piece aluminium block for noise shielding and gas tightness. We constructed several 30cm×30cm prototype chambers using the foils manufactured by CERN GDD group. The initial foils we used were developed with 3M Inc. however, the company subsequently sold their flex circuit division.

We helped to characterize two development versions of KPix chips with GEM chambers to verify the functionality of the chip and the integrated detector system. For this study, we have regularly taken calibration data hourly to see if there are day – night and weekday – weekend effects. This is to fully understand whether there are environmental effects that would impact our measurements with KPix in our labs due to varying noise characteristics. We observed that the mean values of any given KPix channel do not show any systematic day – night dependence or weekday – weekend dependence. The fluctuation in pedestal mean value for each channel is within 3 – 5%. We, however, observe the mean value of the pedestal varies between 20 and 130 ADC counts channel to channel. We also observed that the channel-to-channel variation of the gains vary 5 – 20 ADC counts/fC. These observations have dramatically improved in a newer version of the chip to work with our prototype GEM detectors.

The next generation prototype 30cm×30cm GEM detector prototype was integrated with a KPix V7 chip. We characterized the prototype detector on the bench using various radioactive sources, including ⁵⁵Fe X-ray source, ¹⁰⁶Ru, ⁹⁰Sr and cosmic rays. Our prototype chambers use Ar-CO₂ mixture in 80/20 proportion. Figure 2.(a) shows our cosmic ray test stand with KPix the FPGA and interface board showing in the picture. The inset shows the chamber integrated with the KPix chip while Fig. 2.(b) shows a schematic circuit diagram of the KPix chip which shows the switchable gain and integrated

Figure 3. (a) Characteristic Fe55 X-ray peaks as a function of HV across the entire detector system (b) Measured detector gain obtained from Fe55 source runs as a function of potential across each GEM foil (c) Cosmic ray hit scatter plot of the 64 channel GEM detector. The trigger consisted of coincidences of two 2cmx3cm counters arranged perpendicular to each other, shadowing 2cmx2cm area in the center. (d) The lego plot of the cosmic ray hit map.



trigger logic. This new version of the KPiX chip was modified to accept random triggers (at the cost of duty factors) to compensate the originally designed accelerator based clock from the International Linear Collider (ILC), allowing the triggers for cosmic ray and beam tests.

Figure 3.(a) shows ^{55}Fe X-ray spectrum as a function of high voltage applied across the entire detector system. The spectra show expected behavior, the peak from the 5.9KeV X-ray shifts to higher output charge values as the voltage increases, indicating the increased detector gain. Fitting a Gaussian to the 5.9KeV peak and comparing the resulting output charge with the expected number of ionization electrons in the drift gap, we obtained the gain of the chamber as a function of the potential difference across each of the two GEM foils in the detector, as depicted in Fig.3.(b). The measured gain is consistent with other measurements of double GEM detectors, taking into account the gas composition.

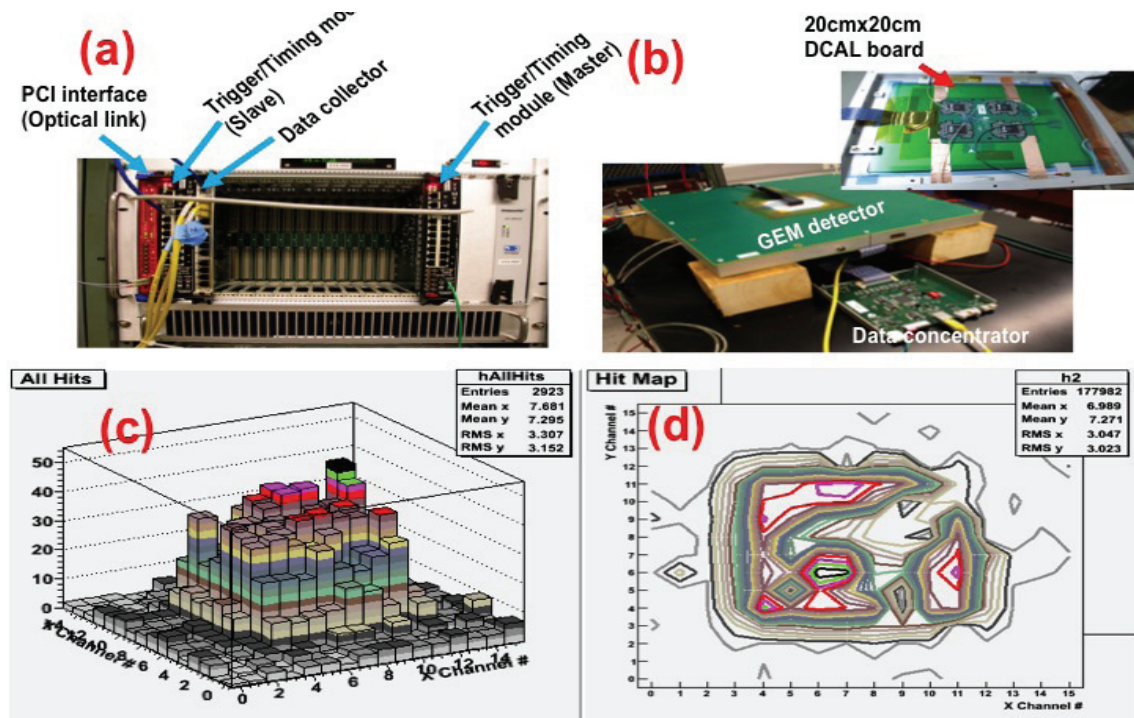
We took cosmic ray data using two 2cm x 3cm counters arranged perpendicular to each other but sandwiching the detector to ensure the center 2cm x 2cm trigger area. Figure 3.(c) shows the scatter plot of the cosmic ray hit distributions, and Fig. 3.(d) shows the lego plot of the cosmic ray hit, clearly demonstrating the area shadowed by the trigger counters.

Unfortunately, in the process of preparing for beam tests originally planned for January 2011, the last KPiX 7 chip stopped functioning late 2010. We suspect the chip's demise was caused by sparks from the detector. This incident forced us to switch over to the 512 channel KPiX9 chip. This chip was integrated to the existing 64 active channel anode board to save cost. At the time of this presentation, we had characterized the new chip and were taking cosmic ray data with the benefit of the strong collaboration between UTA and SLAC teams.

4. Integration with One Bit DCAL Chip

Since, ultimately, a GEM-based DHCAL could be read out using single-bit per channel electronics, as

Figure 4. (a) DCAL DAQ system based on VME-PCI readout system. (b) 20cmx20cm DCAL readout board with 256 channel readout capability along with the GEM detector with full DCAL integration connected to the DCAL DAQ system (c) Lego plots of cosmic ray hits triggered with 10cmx10cm cosmic trigger (d) X-ray image of a wrench as a bench test after the integration of the DCAL electronics.



opposed to analog KPix readout with thresholds applied offline, we have also carried out tests of our GEM chambers using the DCAL chip developed by the Argonne National Laboratory (ANL) and Fermi National Accelerator Laboratory (FNAL) teams. DCAL chip has 64 readout channels and have been used to read out the 1m^3 RPC DHCAL prototype.

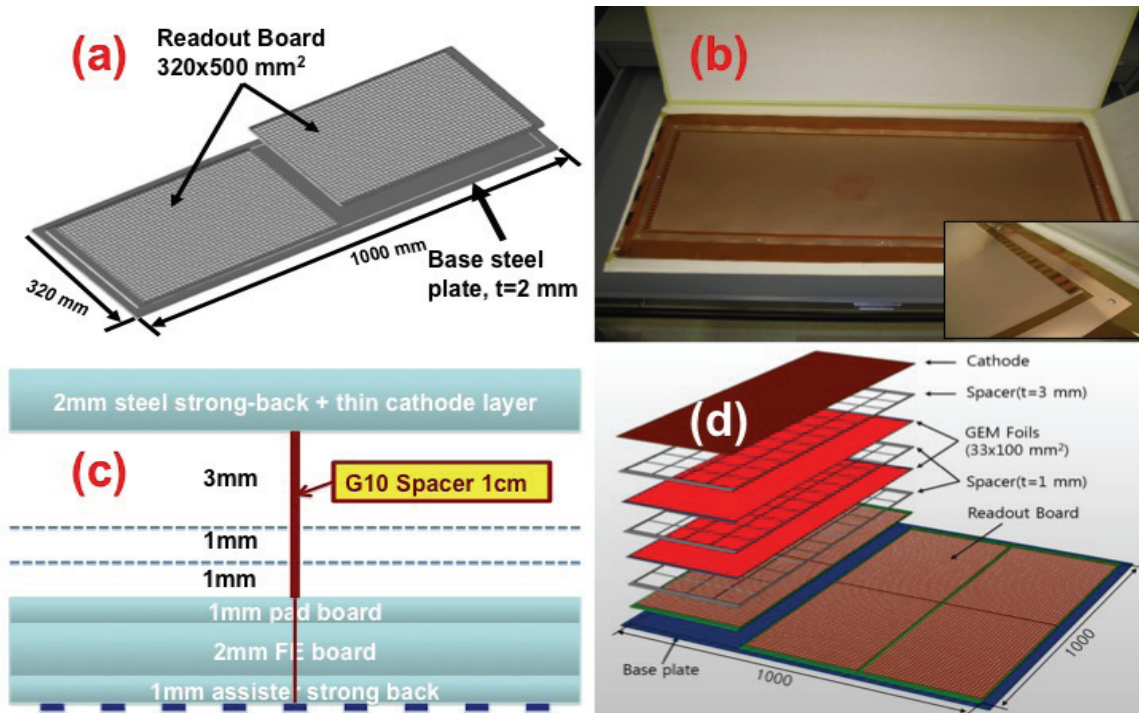
Figure 4.(a) shows a VME crate with various DCAL DAQ system components integrated into it. This system has the capability to expand to a large number of channels. Figure 4.(b) shows a $20\text{cm} \times 20\text{cm}$ anode board with 4 DCAL chips to read out a total of 256 channels interfaced to $30\text{cm} \times 30\text{cm}$ dummy board with integration notches for gas tightness. This interfaced anode board is integrated into the $30\text{cm} \times 30\text{cm}$ GEM prototype detector as shown in the photo.

We performed noise scans of the boards to determine the optimal threshold for each of the two DCAL boards we have integrated with the chambers. The threshold turns out to be on the order of 30 DAC counts which correspond to about a 9 fC charge threshold. Once the threshold was determined we took radioactive source data as well as cosmic ray data with the DCAL readout system. Figure 4(c) shows a lego plot of the hits from cosmic rays triggered by a $10\text{cm} \times 10\text{cm}$ scintillation counter trigger. Figure 4(d) shows a contour plot of an X-ray image of a wrench taken with an elevated ^{55}Fe source that illuminated the entire detector with the wrench blocking part of the detector. Although it is not quite clear due to the coarse readout pad size of $1\text{cm} \times 1\text{cm}$, one can make out the shape of the wrench. These exercises demonstrated the functionality of the DCAL readout system integrated with GEM prototype detectors. Given this, we built a total of three DCAL chambers to expose to particle beams in August 2011 at the Fermilab Beam Test Beam Facility.

5. Development of Large Scale GEM Detectors

The next phase is the development, characterization and construction of the full scale GEM chambers for DHCAL. We plan on constructing $1\text{m} \times 1\text{m}$ chambers using three $1\text{m} \times 33\text{cm}$ unit chambers as shown in Fig.5(a). Together with CERN GDD workshop, we have developed $1\text{m} \times 33\text{cm}$ GEM foils

Figure 5. (a) A schematic diagram of a $1\text{m} \times 33\text{cm}$ unit chamber with base steel plate and two half chamber length anode boards. (b) A photo of a $1\text{m} \times 33\text{cm}$ GEM foil developed jointly with CERN GDD workshop. (c) Cross section of a $1\text{m} \times 33\text{cm}$ unit chamber (d) A schematic diagram of a $1\text{m} \times 1\text{m}$ plane that consists of three unit chambers



for these unit chambers.

Five of the first development samples were produced using a one-side etching technique and were delivered to UTA. Figure 5(b) shows a photo of one of the $1\text{ m} \times 33\text{ cm}$ foils. These foils consist of 31 independent HV strips that run along the length of the foil. We developed a foil qualification procedure based on the leakage current on each of the 31 strips, the amount of time needed for each strip to saturate, and the number of strips with saturation time less than 2000 seconds. We categorized the five foils at three different levels using the criteria described above: pass-high for foils with the qualification ready to build a detector, pass-med for foils with a small number strips that do not pass the criteria and fail for the foils that have large number of failed strips. Two of the foils passed with pass-high and the other two passed with pass-med while the last foil was not tested since it failed CERN GDD qualification.

Figure 5(c) shows a cross section of a $1\text{ m} \times 33\text{ cm}$ unit chamber. We originally planned on using a large scale G10 spacer with a 1cm bar in the center to provide a mechanical support to the two $32\text{ cm} \times 50\text{ cm}$ anode boards. This would maintain the mechanical integrity of the chamber and gas tightness. Through the discussion with the ANL team, we started considering direct gluing of the two boards on the edges. We will have to test and make sure that this scheme provides sufficient mechanical integrity and gas tightness. Three of the unit $1\text{ m} \times 33\text{ cm}$ chambers will make up a $1\text{ m} \times 1\text{ m}$ detector plane, using a $1\text{ m} \times 1\text{ m}$ steel base plate as shown in Fig.5(d).

6. Future Plans

We will develop the mechanical structure, the electronic readout board schemes and the schemes for integrating the three unit chambers into one $1\text{ m} \times 1\text{ m}$ chamber. We plan to construct these unit chambers through 2013. Through the construction stage, we will test these unit chambers with source, cosmic rays and with beams. We will then put a minimum of five of these $1\text{ m} \times 1\text{ m}$ chambers when possible into the CALICE [15] beam test calorimeter stack in mid 2014 to late 2015. The primary goals of this beam test are 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 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 used in many previous beam tests.

The above plans for GEM DHCAL development can be organized in four phases:

- Phase I: Through late 2011, Completion of $30\text{ cm} \times 30\text{ cm}$ chamber characterization and DCAL readout integration
 - At the time of writing this proceeding, we have performed a two-week long beam test at FTBF. We exposed a total of five chambers, one $30\text{ cm} \times 30\text{ cm}$ chamber with KPix9, three $30\text{ cm} \times 30\text{ cm}$ chambers with DCAL and one $3\text{ cm} \times 3\text{ cm}$ chamber with in-house electronics for a medical imaging amplifier.
 - Completion of $1\text{ m} \times 33\text{ cm}$ foil evaluation
- Phase II: late 2011 – early 2013, $1\text{ m} \times 33\text{ cm}$ unit chamber development and characterization
 - Begin construction of two $1\text{ m} \times 33\text{ cm}$ unit chambers, ideally one with KPix and another with the DCAL readout system.
 - Bench test unit chambers with radioactive sources and cosmic rays followed by a beam test
 - Begin construction of a $1\text{ m} \times 1\text{ m}$ plane
- Phase III: early 2013 – mid 2014, $1\text{ m} \times 1\text{ m}$ detector plane construction
 - Construct six unit chambers with DCAL readout system two $1\text{ m} \times 1\text{ m}$ planes
 - Characterize $1\text{ m} \times 1\text{ m}$ planes with cosmic rays and particle beams
- Phase IV: mid 2014 – late 2015, $1\text{ m} \times 1\text{ m}$ plane GEM DHCAL performance tests in the CALICE stack

- Complete construction of five $1\text{ m} \times 1\text{ m}$ detector planes
- Insert five $1\text{ m} \times 1\text{ m}$ planes into the existing CALICE stack and perform beam tests with either Si/W or Si/Scintillator ECAL along with RPC or other planes in the remaining HCAL

Finally, we have been considering an alternative to the standard GEM foil technology. The “Thick-GEM” (TGEM) [16,17] has been shown, in a single layer, to 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. We are collaborating with the Weizmann Institute to work on production and prototyping of GEM chambers using large scale TGEMs. The TGEM team also has made significant progress and presented their results at this conference [19].

7. Conclusions

The UTA HEP group has made significant progress in development and understanding of $30\text{ cm} \times 30\text{ cm}$ double GEM chambers. We have successfully integrated these prototype chambers with the 13-bit KPix analog readout board as well as one bit DCAL readout boards. We have characterized the latest 512 channel KPix9 chips and have characterized the GEM chamber on the bench using various radioactive sources and cosmic rays. We plan on conducting beam tests using four $30\text{ cm} \times 30\text{ cm}$ chambers, one with 13bit KPix and three with 1 bit DCAL readout system. We have qualified the first set of 5 large GEM foils of dimension $33\text{ cm} \times 1\text{ m}$. We have completed the design of G10 spacers for the unit chamber and are preparing a clean room for foil certification and chamber construction. We are working on mechanical design for $33\text{ cm} \times 1\text{ m}$ unit chambers and $1\text{ m} \times 1\text{ m}$ DHCAL plane. Finally, we are working with Weizmann Institute for using large scale TGEM for DHCAL.

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