PROJECT DESCRIPTION and STATUS REPORT

Development of a Digital Hadron Calorimeter for the Linear Collider Using Gas Electron Multiplier Technology

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Project Overview

The precision measurements of physics topics at the International Linear Collider demand unprecedented energy resolution of jets. The Particle Flow Algorithm (PFA) [1] approach is a solution that could be used to achieve such a jet energy resolution. In order to take full advantage of a PFA, it is of critical importance to minimize contributions to the energy resolution due to confusion in track-energy cluster match. 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 fine readout granularity. Reading out in such a high granularity in analog mode could make the cost of the calorimeter prohibitively high. One bit readout per cell would reduce the total number of digital bits dramatically and thus provide the possibility of reducing the cost for readout electronics. However, we will also discuss analog readout later in the context of the SLAC KPiX chip.

Gas Electron Multiplier (GEM) [2, 3] is a detector technology which can be used in a high granularity calorimeter. Over the past several years the University of Texas at Arlington (UTA) team and collaborators from the other institutions listed have been developing a digital hadronic calorimeter (DHCAL) [4 – 6] using GEM as the sensitive gap detector technology. DHCAL is a solution for allowing PFA to be used in precision jet energy measurement. 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 a resistive plate chamber (RPC) [7, 8]. It operates at a relatively low voltage across the amplification layer, can provide high gain using a 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 1cm×1cm pads at zero volts. The potential differences, required to guide the ionization electrons, 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. GEM design allows a high degree of flexibility with, for instance, possibilities for microstrips for precision tracking layer(s), variable pad sizes, and optional initial ganging of pads for eventual finer granularity future readout if required and allowed by cost considerations. Figure 1.(a) depicts how the double GEM approach can be incorporated into a DHCAL scheme.

Results of Initial GEM Studies

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 were read out using the QPA02 chip originally developed by Fermilab for Silicon Strip Detectors. The gain of the chamber was determined to be of the order 3,500, for a 70% Ar/30% CO_2 mixture, consistent with measurements 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 investigated cross talk properties using the nine $1\,\mathrm{cm} \times 1\,\mathrm{cm}$ cell anode pad layout shown in Fig.1(c). We used collimated gamma rays from a ^{137}Cs source to study signal sharing between adjacent pads.

Beam and Source Test Results

As the first step toward building the full-size ($1\mathrm{m} \times 1\mathrm{m}$) test beam chamber, we developed $30\,\mathrm{cm} \times 30\,\mathrm{cm}$ GEM foils together with Microinterconnect Systems Division of 3M Corporation. A foil is divided into 12 independent HV strips for operational safety (we had to disconnect a few strips during beam test experiments). For mechanical

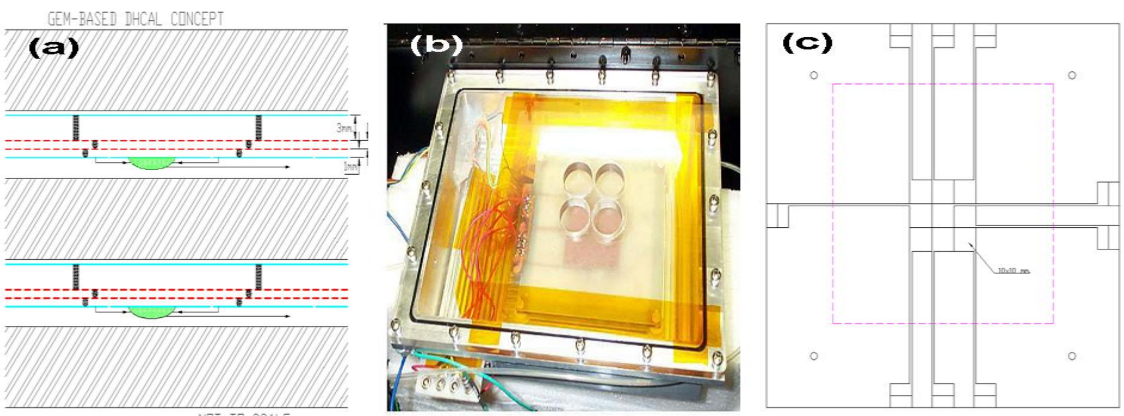

Figure 1. (a) GEM DHCAL concept diagram (b) UTA GEM prototype chamber constructed with $10\,\mathrm{cm} \times 10\,\mathrm{cm}$ CERN GDD GEM foils (c) Prototype readout anode pad with nine $1\,\mathrm{cm} \times 1\,\mathrm{cm}$ cells

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. We constructed several prototype chambers using these foils and a readout board with $1cm \times 1cm$ pads, and exposed them in various particle beams. These chambers were read out using the 32-channel QPA02 chip-based Fermilab preamp cards.

We conducted three beam tests to measure the rate capability of the chamber, its MIP characteristics, cross talk between the channels, and occupancy. The output signals from the amplifier cards were 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 $30cm \times 30cm$ prototype chamber took place in May 2006 at a high flux beam which 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. The chamber was able to see the beam clearly and provided a good measure of the time structure of the beam. Additionally, 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 hits from 10^9 electrons per pad, the chamber responded well to such a large signal, giving us confidence that the chamber will function well in the ILC environment.

Additional beam tests were conducted at Fermilab's Meson Test Beam Facility (MTBF) [11] in April 2007. We tested a single multi-channel chamber using a 100 channel readout system. Most the useful data was taken 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 were accumulated. Since the DAQ card required a long signal for 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 verification purposes.

The trigger was formed of coincidences of three $1cm \times 1cm$ and two $19cm \times 19cm$ counters to constrain the beam to an area smaller than $1cm \times 1cm$, which was the size of a readout pad. The two $19cm \times 19cm$ counters enveloped the GEM prototype chamber to ensure 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 efficiencies and fractional cross talk ratios. In order to verify the proper functionality of the chamber, we took data using a high intensity Sr^{90} radioactive beta source. Fig. 2.(a) shows the signal without noise subtraction (blue), noise (purple) and noise subtracted signal (red) when 120GeV proton beam is incident on the target pad. The noise subtracted signal distribution demonstrates a Landau shape as expected. Fig. 2.(c) shows the relative efficiency measured on this pad as a function of threshold, which demonstrates that the efficiency is about 98% at 40mV. However, it 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 between the noise subtracted signal distributions from the source and proton beams respectively. 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 being finalized.

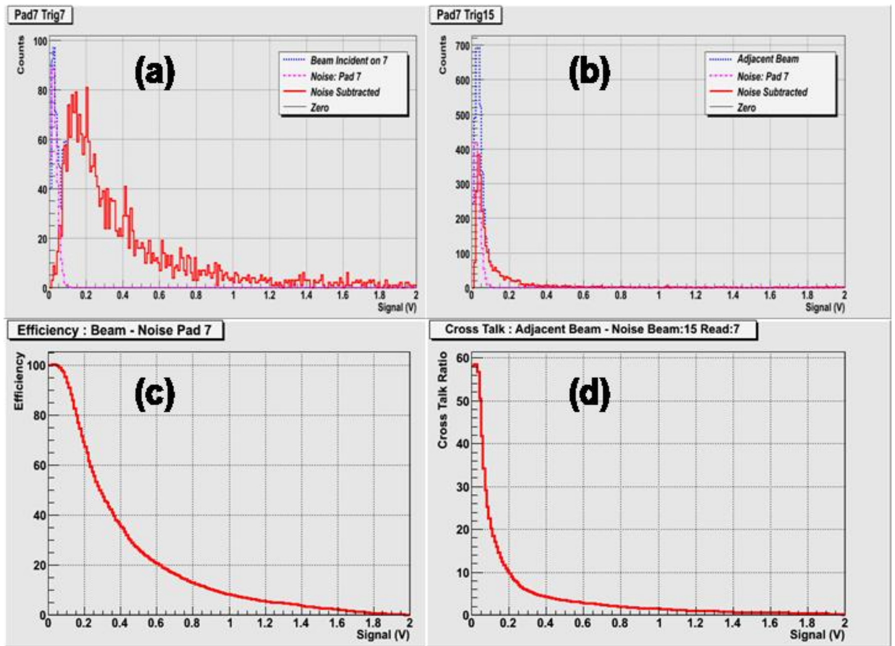

Figure 2. Signal from 120GeV proton (blue), noise (purple) and the noise subtracted beam (red) distributions (a) when the beam is incident to the pad and (b) when the beam is incident to the neighboring pad (c) Relative efficiency (d) % fractional cross talk ratio

In order to measure the cross talk rate, we read out the pad immediately next to the trigger pad. Fig. 2.(b) shows the pulse height distributions of the pad number 7 when beam was incident on an 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.2.(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 being finalized to take into account these different effects Fig. 3.(a) and 3.(c) show the responses of the two channels of the prototype chamber described above to electrons from a Sr^{90} radioactive source. Both channels show the characteristic Landau distributions expected from a gas detector. Figures 3.(b) and 3.(d) show the absolute efficiencies of the chamber for the same two channels as a function of threshold in mV. As can be seen, the chamber demonstrates efficiencies over 99% when the threshold is set at 30mV which is equivalent to 4 fC.

Multichannel Readout of GEM DHCAL Using KPiX

As the next phase, for a full chamber characterization using a multiple channel readout system, we have been working with the high density analog readout system, KPiX which is being developed at SLAC, and is described in detail in Ref. [12]. As described later in this proposal, we plan to conduct further beam tests using KPiX once we complete integrating the chip with our GEM chambers and fully characterize its behavior in bench tests. The KPiX readout chip was originally developed for silicon-tungsten (Si/W) electromagnetic calorimeter (ECAL) [13, 14]. The chip has been modified to include a switchable gain to accommodate small signals from a GEM chamber. KPiX is being considered as the standard front-end readout device for most of the major SiD [15] subsystems. It offers a 4 event deep pipeline, with a 13-bit Wilkinson ADC on each channel. A decision, based on a combination of hardware tests, PFA studies and costs, will be taken later about the final use of KPiX for the hadron calorimeter.

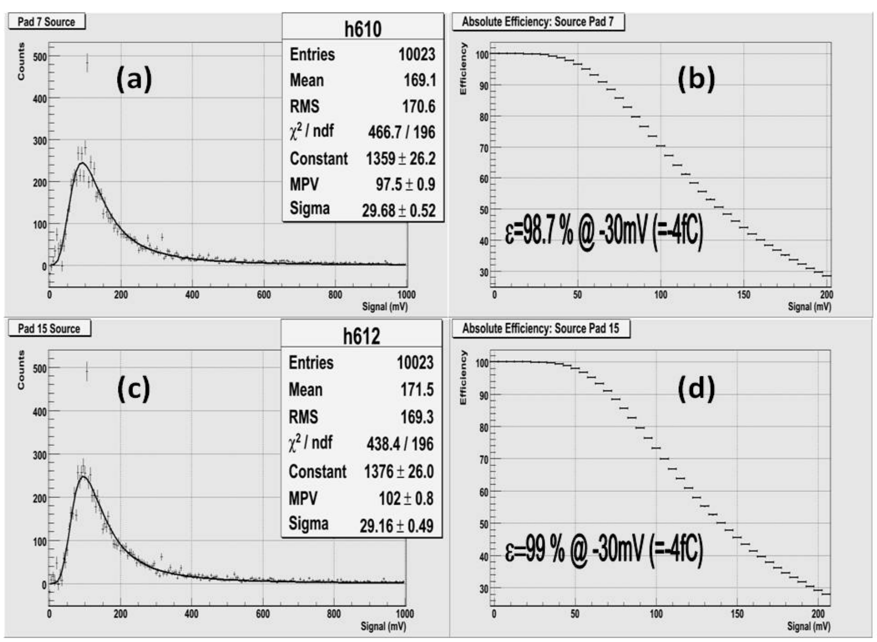

Figure 3. (a) and (c) responses of two channels to Sr90 source in mV; (b) and (d) Absolute efficiencies of the same two channels as a function of threshold in mV

The first study we performed was the characterization of the calibration parameters of the KPiX v4 chip with a GEM chamber. For this study, we took calibration data hourly for 19 hours and 24 hours on two different days to see if there are day – night and weekday – weekend effects. This was to fully understand whether there are environmental effects that would impact our measurements with KPiX v4 in our labs. We observed that the mean values of any given KPiX v4 channels 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, observed the mean values of the pedestal vary between 20 and 130 ADC counts channel to channel, as shown in Fig.4.(a). We also observed that the channel to channel variations of the gains vary 5 – 20 ADC counts/fC, as shown in Fig.4.(b). This channel to channel gain variation has been reduced by a factor of two in the newest version of the KPiX chip (v7). These observations have been communicated to SLAC team, and we anticipate the next generations of the chip will have far less variations.

Fig. 4.(c) shows the signal read out from the GEM chamber with the KPiX chip from a channel right under the source. As can be seen, the plot shows a large pedestal peak

near 0 fC with the long tail that signifies the signal from Sr^{90} source. Since this version of the KPiX chip was designed specifically to work in the International Linear Collider (ILC) operational mode, its trigger is synchronized to the ILC accelerator clock which is expected to send the signal of beam arrival ahead of collisions. Due to this feature of the chip's triggering scheme and to the fact that we took data with Sr^{90} source which emits low energy electrons that are difficult to trigger, the readout chip ran in a periodic reset mode that integrates the charge in regular intervals independent of the existence of the actual charge in the chamber.

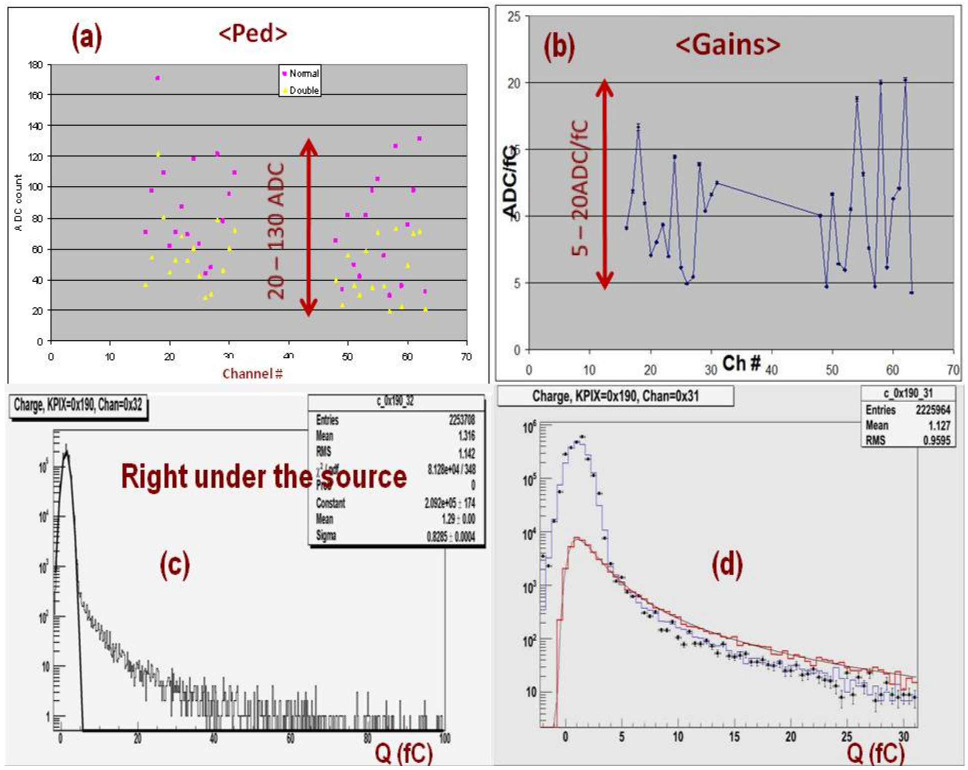

Figure 4. (a) The pedestal mean value vs channel number (b) Mean value of the electronics gain vs channel number (c) Mean pedestal subtracted and electronics gain corrected charge distribution from Sr90 source run (d) Extracted charge distribution from the GEM chamber (red) from the inference method using the simulation (blue) and its description of the data (solid circles). The good distribution of the data from the simulation demonstrates that the extracted signal represents the chamber responses well.

In order to extract the charge distributions from Fig.4.(c), we developed an inference method based on simple simulation of the KPiX charge integration scheme, the actual pedestal distribution of the channels from previous calibration runs, the simulated pulse shape of the minimum-ionizing particle and the charge distributions from the previous beam test measurements. We simulated the KPiX charge integration within a fixed amount of time (333ns – the ILC beam crossing interval) starting randomly with respect to the signal pulse. We then let the normalization of the Gaussian pedestal distributions and the most probable value and the width of the charge distributions float until the resulting output charge distribution describes the data distribution well. Fig.4.(d) shows the data from the channel under the source in solid circle, the final simulation results in blue histogram and the extracted GEM chamber response in red histogram. As can be seen, the fact that the form of the data is well described by the simulation gives us confidence that the extracted chamber response is real.

We, however, noticed that the most probable value of the extracted GEM chamber response is 1.9fC which is about a factor of 10 smaller than what we observed in previous source and beam tests. Upon detailed investigation of the chamber structure, which was to give flexibility in modification of the chamber for KPiX v4, it was determined that this does not provide an adequate level of gas in the active volume of the chamber since the structure imposes a large resistance to the gas diffusion; thus most of the gas flows following the direction around the active chamber volume. As a result, when we took the source data, the charged particles traversing through the detector volume did not produce sufficiently large amounts of ionization. Given this feature, we modified the chamber so that the gas is forced to be directly injected into the active volume and diffuse out to the remaining volume of the chamber through tubing laid within the chamber active volume.

We took cosmic ray data to make sure that the chamber is producing sufficiently large signals and have indeed observed the expected size signals from the chamber. We are now working on integrating this new chamber with the new version (v7) of KPiX chip (KPiX7). We are in the process of characterizing the new version of the KPiX chip and are taking cosmic ray and source data to fully characterize the chamber with KPiX v7 chip.

Summary of Project Status

The UTA HEP group has made significant progress using the $30cm \times 30cm$ GEM foils developed in collaboration with the 3M Inc. We have been working on integrating the GEM chamber with the KPiX analog readout chip. We have characterized the previous version (v4) of the KPiX together with a GEM chamber and extracted the signal from a Sr^{90} radioactive source. We are working on integrating the chamber with the latest version (v7) of the KPiX chip that allows external trigger input. We describe our plans in FY2009 – 2011 in the sections below.

FY2009 Project Activities and Deliverables

- **Full Characterization of 30cm x 30cm GEM chamber with KPiX7 Readout**

The SLAC team has provided an anode board with the new 64 channel KPiX v7 chip. This new version provides HV discharge protection as well as the capability of external trigger input which will help testing dramatically. Based on the experience from the previous version of KPiX chip, we have made a change in the gas distribution system to ensure fast gas replacement and optimal ionization and signal induction levels. Now that we have successfully observed signals from Sr^{90} radioactive sources, we are ready to take data for full characterization of our double GEM chamber prototype read out by the analog KPiX chip.

As the next step, we will construct a new $30\,cm \times 30\,cm$ chamber with the optimal gas distribution and a KPiX v7 readout board. We will understand the noise characteristics of the chamber and will perform source tests. We will then take cosmic ray data for MiP characterization, noise characteristics, and cross talk, on the bench at UTA - reading out 64 channels. Once we are confident with these results, we will expose the chamber in particle beams for high statistics chamber characterization, measuring response uniformity, noise rates, cross talks, absolute efficiencies, and gains.

- **Development of 100cm x 33cm Large GEM Foils and Chambers**

We plan to construct a total of five $100\,cm \times 100\,cm$ GEM chamber planes to demonstrate performance of GEM active layers in a hadronic calorimeter. We will be working on development of smaller unit chamber of size $100\,cm \times 33\,cm$ (with $96\,cm \times 32\,cm$ active area), three of which will make up one $\sim 100\,cm \times 100\,cm$ plane. While we had been working on development of $30\,cm \times 30\,cm$ GEM foils successfully with the 3M Inc., they decided to close their micro-flex circuit division in late 2007. For this reason and because the CERN GDD workshop has been working on developing cost effective technology to produce large size GEM foils, we are now working with this workshop on the design of a $100\,cm \times 33\,cm$ GEM foil silkscreen. The CERN GDD work shop estimates a total production time of eight weeks for the first set of 20 large GEM foils after the finalization of the silkscreen. We are currently working with CERN to finalize the design of the silkscreen that is optimal for our prototype detectors. This work is being carried out in the context of the RD51 – Micro-Pattern Gas Detector Collaboration, of which UTA is an active member (A. White is a RD51 Management Board member).

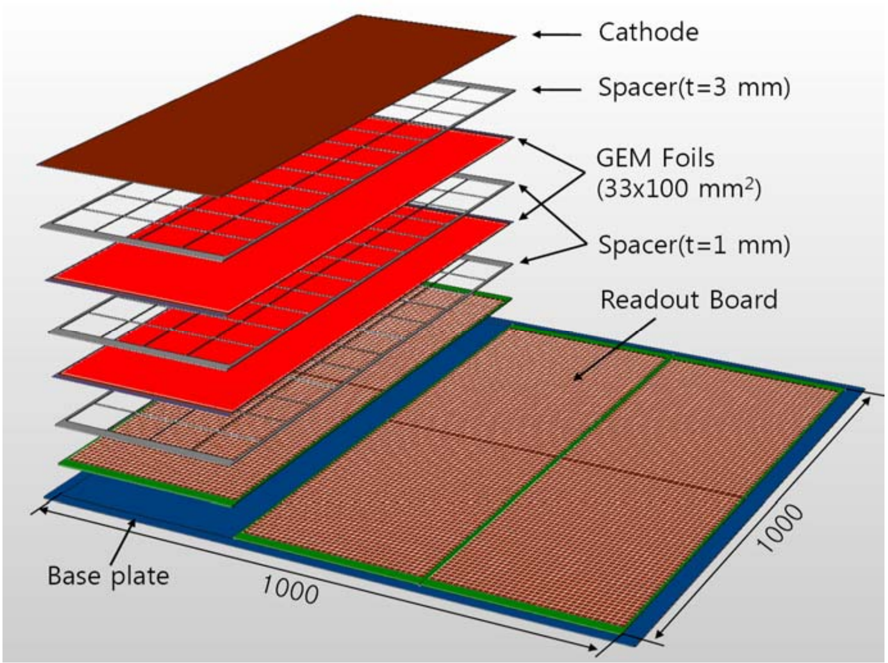

Figure 5. A schematic diagram of a $100\,cm \times 100\,cm$ double GEM detector plane. Three of unit chambers of size $100\,cm \times 33\,cm$ will be assembled on a 2mm steel plate to make up one $100\,cm \times 100\,cm$ GEM plane. The figure also shows the anode board structure where two boards $50\,cm \times 33\,cm$ make up one unit chamber.

As part of the effort for constructing $100\,cm \times 100\,cm$ GEM planes, we will work on development of mechanical structure, the electronic readout board schemes with the SLAC team, and the schemes for connecting the three unit chambers to form one $100\,cm \times 100\,cm$ detector plane. Each of the $100\,cm \times 33\,cm$ unit chambers will have $96\,cm \times 32\,cm$ active area, leaving two 1cm gaps on each of $100\,cm \times 100\,cm$ plane in between unit chambers. As shown in Fig. 5, we plan to use a 2mm thick $100\,cm \times 100\,cm$ area steel plate to assemble three of these unit chambers into one $100\,cm \times 100\,cm$ detector plane with strong mechanical support.

Once we finalize the mechanical structure for the unit chamber of size $100\,cm \times 33\,cm$, we will construct one prototype chamber using the 256 channel KPiX v8 analog readout chips, to be available by mid-2009, and a readout anode board of size $50\,cm \times 33\,cm$. We anticipate the first chamber to be ready for testing in late 2009. We will characterize the chamber and the chip using source and cosmic ray at UTA. Once the chamber is characterized on the bench, we will expose the chamber to particle beams.

- **Anode Board for 1m x 33cm GEM Unit Chamber with KPiX v8**

We have been working with the SLAC KPiX electronics team led by M. Breidenbach in using the analog system for GEM chamber signal readout. After several months of understanding the performance of the electronics with $30\,\text{cm}\times 30\,\text{cm}$ GEM chambers, we will be at the point to take data using KPiX v8 readout chips. Two $50\,\text{cm}\times 33\,\text{cm}$ anode boards will make up one $100\,\text{cm}\times 33\,\text{cm}$ anode boards for a unit chamber. Each half anode board will be read out by six 256 channel KPiX v8 chips.

Project Activities and Deliverables Beyond FY2009

- **Completion of Construction and Characterization of 100cm x 33cm Unit Chamber**

In the case that the development of $100\,\text{cm}\times 33\,\text{cm}$ unit chamber and the characterization process does not finish in FY2009, we will complete this process as part of the FY2010 activities.

- **Large Thick-GEM prototype chamber in 2010**

As an alternate, cost effective solution for regular thin GEM foils, we have been continuing to pursue the development of thick-GEM's (TGEM) [16, 17]. In addition to TGEMs that are made of normal PCBs, a new development effort has been made on Resistive Electrode TGEMs (RETGEMs) [18]. As a member of the RD51 collaboration, we are working closely with various collaborators on the development of these new TGEMs in small and large scales. In particular, we have been working with the Amos Breskin's group at the Weizmann Institute for large scale TGEM development. These TGEMs are anticipated to become available on a late 2009 or early 2010 time scale. Once TGEMs are tested and certified, we will construct and characterize a prototype chamber on the bench using 64 channel KPiX v7 or 256 channel KPiX v8 analog chips. When this completes, we plan to expose the chamber in the beam for full, high statistics characterization and for comparison of its performance with regular thin GEM chambers. We anticipate this beam test to be on an early or mid 2010 time scale.

- **Completion of Construction of five 100cm x 100cm GEM Planes and DHCAL Beam Test**

As the $100\,\text{cm}\times 33\,\text{cm}$ unit chamber is being fully characterized, we will complete the mechanical design for $100\,\text{cm}\times 100\text{cm}$ GEM active layer planes and construct a total of five of such planes. We will develop a procedure for mechanical construction and quality testing of the planes and will replace five of the forty RPC planes in the existing CALICE[19] calorimeter beam test stack currently located at Fermilab for beam test. The goal of this beam test is to partially measure the performance of a GEM-based DHCAL. This result should be compared to that of a DHCAL with full 40 layer RPCs and other analog HCALs to provide valuable information in overall ILC detector design choices. This beam test will be carried out using either CALICE Si/W or Scintillator/W ECAL and a tail catcher (TCMT), using the CALICE mechanical support structure.

GEM/DHCAL Beam Test Plans

In order to continue testing GEM based DHCAL, we plan for the future particle beam tests of our GEM chambers in phases as listed below.

- Phase I: Chamber characteristics
  - A prototype chamber with dimension $30\,\mathrm{cm}\times 30\,\mathrm{cm}$ will be constructed with the 64 channel KPiX v7 analog chips being characterized at SLAC and at UTA.
  - The primary goal of the test is to exercise the newly developed and bench-characterized KPiX v7 chip in particle beams with the trigger system synchronized to the accelerator clock, and fully characterize the chamber with KPiX readout chips.
  - This test will be performed at Fermilab's MTBF in early summer 2009.
- Phase II: Unit chamber ($100\,\mathrm{cm}\times 33\,\mathrm{cm}$) beam test
  - We will construct a total of fifteen $100\,\mathrm{cm}\times 33\,\mathrm{cm}$ unit chambers using the CERN-developed $100\,\mathrm{cm}\times 33\,\mathrm{cm}$ GEM foils.
  - For readout of these unit chambers, we will be using the next generation 256 channel KPiX v8 chips. Twelve of these chips will be used to readout a unit chamber, six of each mounted on $50\,\mathrm{cm}\times 33\,\mathrm{cm}$ anode board.
  - This test will be performed at Fermilab's MTBF sometime in late 2009 – mid 2010.
  - The goal of this test is to characterize large scale unit chambers built with CERN thin GEM foils.
  - We expect to receive a few large Thick GEM (TGEM) boards in this time period. We will then build a prototype chamber and expose to particle beams for characterization. We will be using 256 channel KPiX v8 chips for this test as well.
- Phase III: Five GEM Plane DHCAL Beam Test
  - We will then construct a total of five $100\,\mathrm{cm}\times 100\,\mathrm{cm}$ chambers, each using three unit chambers.
  - This test will be performed at Fermilab's MTBF on a late 2010 – early 2011 time scale.
  - These chambers will be inserted into the existing CALICE $1\,\mathrm{m}^3$ calorimeter stack as part of the on-going beam testing of RPC based DHCAL.
  - The goal of this test is to partially measure the responses and resolutions of GEM-based digital hadron calorimeter along with RPC planes.
  - This full scale prototype will be tested jointly with CALICE Si/W ECAL and the NIU tail catcher (TCMT), using the CALICE mechanical support structure.

Simulation and PFA development of GEM/DHCAL in the context of SiD

During the past several years, due in part to lack of funds, we have been concentrating on hardware development, rather than both hardware and simulation. While the geometry for the GEM DHCAL layer structure has been provided and incorporated into the SiD detector overall geometry, our previous studies were conducted using an old Mokka TESLA detector geometry. Since the performance of a detector component is only meaningful as an integral part of an overall detector, it is important for our group to obtain funds to resume the performance studies of GEM in the context of SiD, develop simulations for beam test stacks, and to actively participate in Particle Flow Algorithm (PFA) development.

Since GEM is already included in the SiD detector geometry, thanks to Norman Graf's efforts at SLAC, we will start with verifying the implementation of this geometry and conduct performance studies of GEM DHCAL in the SiD context. We will investigate the responses and energy resolutions of single particles to compare the detector's performance to the previous studies and will compare GEM with other detector technologies, such as RPC and scintillator based HCAL.

In addition, given the fact that we will be taking series of test beam runs, we need to prepare simulation packages for beam tests. Since we are part of CALICE, and will be an integral part of the CALICE test beam set up, we can utilize the MC framework that allows an easy integration of our detector geometry for the test beam, especially the run with the full scale $1m^3$ prototype. This will allow our students to exercise their analysis techniques in time for the full scale prototype run.

Since the largest contribution in worsening jet energy resolution in PFA comes from the confusion term that stems from unmatched or mismatched energy clusters, the fine granularity of the calorimeter cells will be of particular importance. However, the studies that have been conducted so far have yet to clearly demonstrate the dependence of PFA resolution on the lateral size of the cells and/or the granularity of longitudinal layers. This probably has to do with the fact that there is no unique PFA that the R&D groups can use as a common tool. This, however, should not stop the groups studying these dependencies with one given algorithm. In addition, the recent completion of a PFA template should certainly be of great help.

Since GEM can essentially provide track position information, it is natural for us to perform the cell dependence study and to provide optimal cell sizes for a PFA detector and other parameters such as absorber thickness, sensitive gap size, on-board readout electronics sizes, and mechanical support structures. These studies will be done, in particular, for GEM DHCAL.

The preparation and verification of simulation packages and studies in optimal detector parameters will allow us to naturally move into the development of PFA in the following years. We will start with developing an H-matrix based electron and photon identification algorithm, taking advantage of experience in ATLAS. This will be tested at the test beam and will be made available to the community for broader use. We will then move into cluster matching algorithm for hadrons, utilizing GEM's fine granularity.

To expedite the use of the beam test data, we will work closely with the SiD software development team and the CALICE software development team to incorporate GEM software into already existing data analysis software. The development of GEM test beam analysis software should begin as soon as possible so that it is prepared in time for the anticipated beam tests of five layers in late 2010 and early 2011.

To summarize, the major deliverables for FY2009 - 2011 in simulation and software efforts are as follows:

- Verification of GEM in the SiD geometry and comparisons of detector performance with previous studies
- Development and verification of PFA with GEM in SiD

- Development of analysis software, and analysis of beam test data

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