Digital Hadron Calorimetry for the Linear Collider using GEM based Technology

1. University of Texas at Arlington, 2. University of Washington, 3. Changwon National University, Changwon, Korea, and 4. Tsinghua University, China.

Andrew Brandt[1], Kaushik De[1], Venkat Kaushik[1], Jia Li[1], Mark Sosebee[1], Andy White[1,a], Jae Yu[1,b], Tianchi Zhao[2], Changhie Han[3], Li Jin[4], Yulan Li[4], Yongfang Lai[4], Yue Qian[4]

[a] GEM detector contact: awhite@uta.edu, (817) 272-2812, (817) 272-2824 (FAX)

[b] Simulation & Software contact: jaehoonyu@uta.edu, (817) 272-2814, (817) 272-2824 (FAX)

1. Introduction. GEM-based Digital Hadron Calorimetry.

We have been developing the implementation of digital hadron calorimetry for future Linear Collider detectors using Gas Electron Multiplier technology [1]. This is a critical and essential development for future experiments that will rely on the Energy Flow Algorithm [2] 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 multiple GEM foils (double or triple). The amplified charge is collected at the anode, or readout pad, layer, which is at ground potential. This layer is subdivided into the small (~1cm x 1cm) pads needed to implement the digital approach.

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 signals are amplified, discriminated, and a digital output produced. The 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 required by cost considerations. Fig.1 shows how the GEM approach is incorporated into a digital calorimeter scheme.

2. Progress report on GEM/Digital Hadron Calorimetry Development

2.1 Results from GEM prototypes

We have benefited from LCRD and DoE/ADR support for the past two years. Previously we reported initial results on signal characteristics and gain from a small prototype GEM detector. Here we give an update of results from the past year. These have been collected using the detector shown in Fig.2, using the anode pad layout shown in Fig.3.

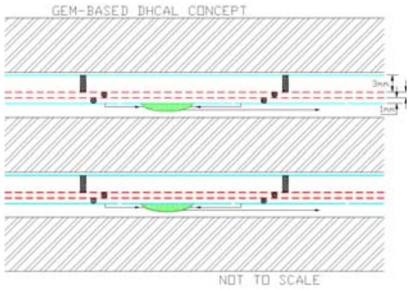

Figure 1. GEM-based digital calorimeter stack.

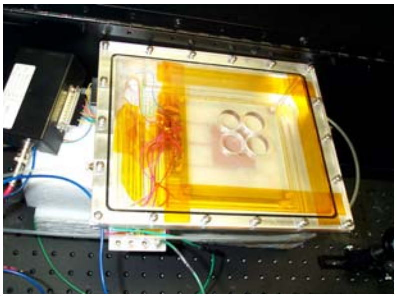

Figure 2. Prototype GEM detector.

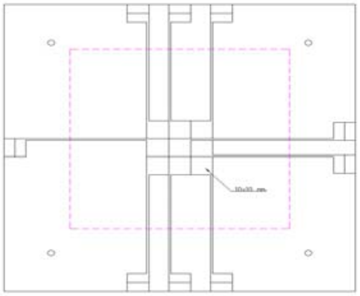

Figure 3. Nine pad anode layer.

Using multi-pad readout we have studied the crosstalk between neighboring cells. A typical (but rarely occurring) situation is shown in Fig.4. The large peak is the signal on the central pad of the 3x3 arrangement. The up-down peaks of the second trace are the crosstalk signal on an adjacent pad. We have reproduced these peaks using direct signal generator pulse injection. The results are shown in Fig.5. We have also used collimated gamma rays from a Cs^{137} source to study signal sharing between adjacent pads. A typical sharing of signals between pads is shown in Fig.6. Note the absence of a "down" peak as seen for a crosstalk signal.

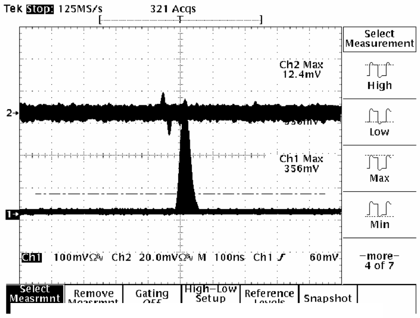

Figure 4. Crosstalk signal.

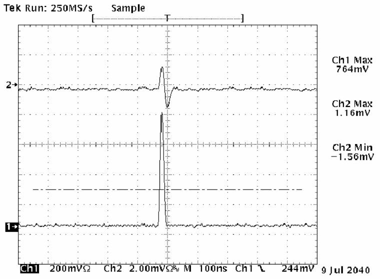

Figure 5. Generation of crosstalk.

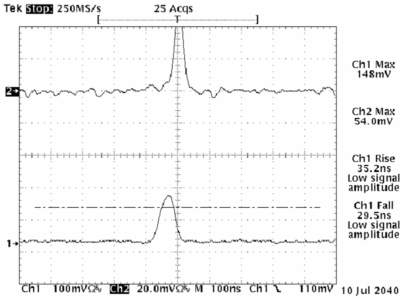

Figure 6. Signal sharing.

We have also looked into the effects of changing the proportion of Argon in our Argon-CO_2 gas mixture. We find that we obtain a factor of three increase in signal size changing from a 70/30 mixture to an 80/20 mixture. The latter mixture has given very stable detector performance over weeks of operation with no discharges. We therefore expect minimum signal sizes for MIPs in the range 15-20fC using the 80/20 mixture; minimum signals in this range ease the design of the front-end ASIC described below.

2.2 Development of large-area GEM detectors

For the full-size testbeam module, and final elements of a GEM-based DHCAL system, we are targeting ~1m x 30cm detector panels. We have been working in two main areas: the mechanical aspects of large GEM-layer assembly, and the fabrication of large area GEM foils. The layer assembly has required development of tools to hand large area foils, and present them flat for integration into a detector. We have also developed initial components for the detector walls (1mm and 3mm heights are required), gas in/outlets, and spacers to maintain the separation of the foils. Further valuable information will be learned in the assembly of 30cm x 30cm detectors, for which 3M foils will soon be tested at UTA and Tsinghua University, China. Figure 7 shows a large test GEM mechanical assembly which is close to its completion.

Figure 7. Large Area mechanical prototype.

Figure 8. 3M Gem foil roll.

The second principal development involves production of large area GEM foils ~1m x 30cm. We have been working with the Microinterconnect Systems Division of 3M Corporation, Austin, Texas to extend their production capability to large area foils. At present their etching window is approximately 30cm x 30cm – to be used for our next prototype. A modification will allow sections of 1m x 30cm to be produced. Verification is needed of the required GEM hole alignment between the two sides of a foil to meet tolerance. The processing system shown in Fig. 8 can produce up to 500 feet of foils on a single roll.

3.0 Progress Report on Simulation and Detector Performance Results

3.1 Implementation of GEM Geometry

The UTA group has successfully implemented a double GEM layer geometry into the existing Mokka [3], a GEANT 4 [4] based simulation package, replacing the scintillation counter sensitive layers in the TESLA TDR hadronic geometry (stainless steel/ scintillation counter) with the double GEM layer structure shown in Fig.9.a. We retained all other detector structure the same as in TESLA TDR detector design [5]. In order to optimize computer CPU resources, we have implemented a simplified version of the GEM instead of detailed geometry as shown in Fig.9.b. A comparison using single 75 GeV pion events shows virtually identical energy deposit in half the CPU time for the simplified mixture version compared to a detailed geometry of a double GEM structure. Based on this study, we have decided to use the simplified geometry for further studies.

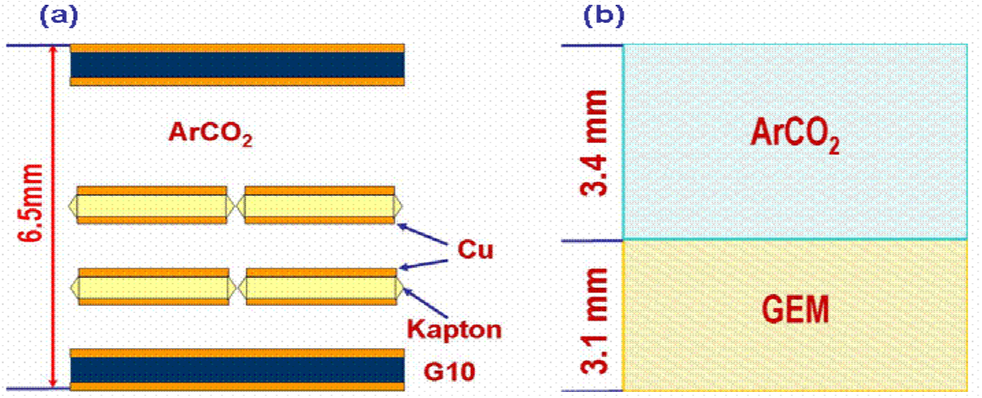

Figure 9. (a) Detailed double GEM geometry. (b) Simplified GEM geometry.

3.2 Double GEM Digital Calorimeter Performance

Using the established simulation and analysis software, we have completed the study of double GEM based calorimeter performances in analog and digital readout modes with a realistic threshold value at 98% of a MIP, using single pion samples whose energies range from 5 GeV to 100 GeV. The intrinsic gain of the double GEM sensitive layers was chosen to be 3000, the value measured from our prototype, which is within 15% of other measurements. The results from these studies have been compared to TESLA TDR detector performance studies based on Mokka. The resolution obtained from our studies of TESLA TDR detector is consistent with results from other studies, if an energy-independent EM and Hadronic relative normalization factor of 0.65 is used.

We used the same data set generated for the analog studies of GEM calorimeter to perform digital studies. Fig.10.a shows a profile plot of E vs N for hit-to-energy-deposit conversion. Fig.10.b shows the scatter plot of energy vs number of hits, which demonstrates the linearity of the detector in its digital readout mode. As expected saturation in the number of cells hit begins to appear at the higher energy deposits due to larger energy densities in a cell. It has been observed in our study that 85% of the cells are hit once for 5 GeV single pion showers while this fraction decreases to 74% for 100 GeV single pion showers. A study of number of hit cell vs layer number for 50 GeV pion shows that it directly mimics the energy deposit distribution along the layer, providing direct evidence and confidence that a GEM based calorimeter can be used as a digital calorimeter properly representing energy deposit of showers. We used the number of hit cells versus energy deposit to extract the hit-to-energy-deposit conversion factor for digital readout mode analysis.

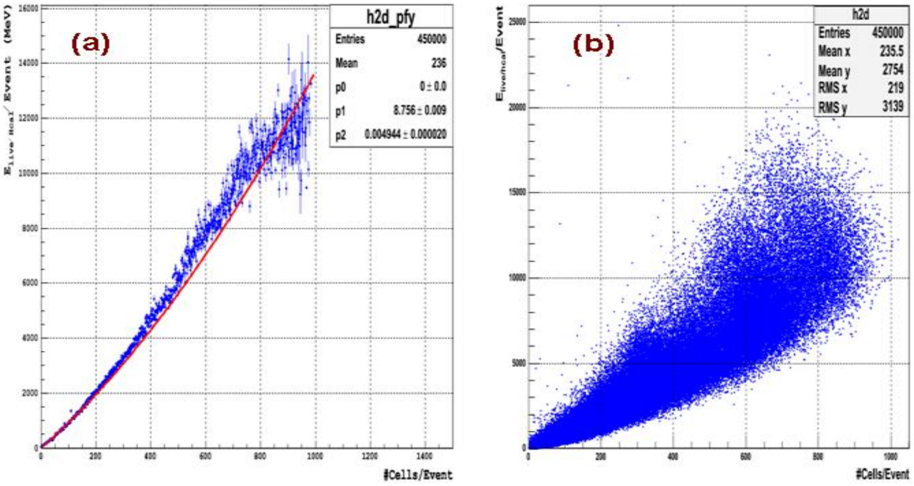

Figure 10. (a) A profile plot of energy deposit vs number of cells hit used for hit-to-energy-deposit conversion. (b) A scatter plot of energy deposit . A saturation at the higher energy deposit is seen.

More sophisticated procedure for fitting the responses from EM and Hadronic components had to be developed to accommodate the changes in energy deposit distributions for analog and digital modes. The energy deposit measured in analog mode shows a remaining large tail due to Landau fluctuations. These large fluctuations are suppressed in digital mode since the tail on higher energy deposit within a cell is still counted as one hit forcing the distribution Gaussian. Fig. 11.a and b show distributions of energy deposit by 50 GeV pions for analog and digital modes, respectively.

Figure 12 shows the energy deposit of a 50 GeV muon in the GEM calorimeter (red

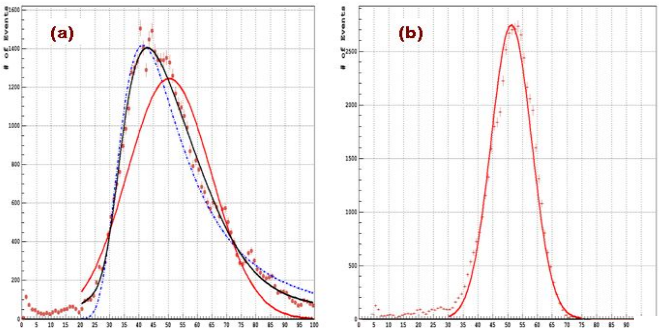

Figure 11. Energy deposit of 50 GeV pions (red circles) in GEM DHCAL (a) in analog and (b) in digital modes.

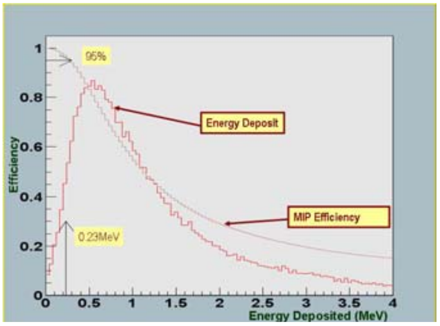

Figure 12. Energy deposition of a 50GeV muon (red histogram) and the cut efficiencies as a function of discriminator threshold (dark red).

histogram) and the MIP efficiency as a function of discriminator threshold (dark red). The arrows indicate the threshold and the corresponding efficiency. From this study we find that 0.23 MeV for muon energy deposit gives 95% MIP efficiency. The performance of GEM DHCAL with thresholds has been completed without incorporating realistic noise measurements. The above studies of GEM DHCAL performance were carried out by two Master's students. The results from the data analysis have been documented in S. Habib's [6] and V. Kaushik's Master's theses [7].

Performance studies show that GEM calorimeter responses for analog and digital are very closed to each other as we expected. The resolution curves of TESLA TDR detector (red) in analog readout mode and GEM calorimeter in analog (blue) and digital (green) modes with 98% threshold are shown in Fig. 13.a. The single pion energy resolution of the GEM digital calorimeter is comparable to that of TESLA TDR and other detector studies (triangles) for most the energy ranges except at low energies. This is reflected in the resolution function as the digital mode showing larger sampling terms (~70%) with relatively smaller constant term. On the other hand, the GEM analog mode resolution is significantly worse than other detectors or than the digital modes. This behavior is caused by the large remaining Landau fluctuation in energy deposit as discussed above.

3.3 Test of Jet Energy Improvements Using EFA and GEM DHCAL

Once the final single particle energy resolution is known, it is straightforward to apply these functions to smear particles in a jet to test the performance of EFA and the given calorimeter technology. We used Pythia to generate $t\bar{t}$ to 6 jet events to test the performance. In order to carry out the study, we had to define a "jet'" in simulated events. In the absence of an official applicable jet algorithm, we took a simple cone algorithm of size ΔR=0.5 around the direction of the final state parton to define a particle jet. We then took each particle and smeared its energy using the parameters of single particle resolution functions, and add all smeared particle energies inside the cone for measured jet energies. This procedure is slightly changed for EFA jet energy resolution. We smeared the energies of all charged particles by an expected tracker momentum resolution, $\Delta p/p = 10^{-5}$, and all electromagnetic particles, including hardons whose final states are EM particles, such as π^0 and η^0, with an EM calorimeter resolution, $15\%/\sqrt{E}$.

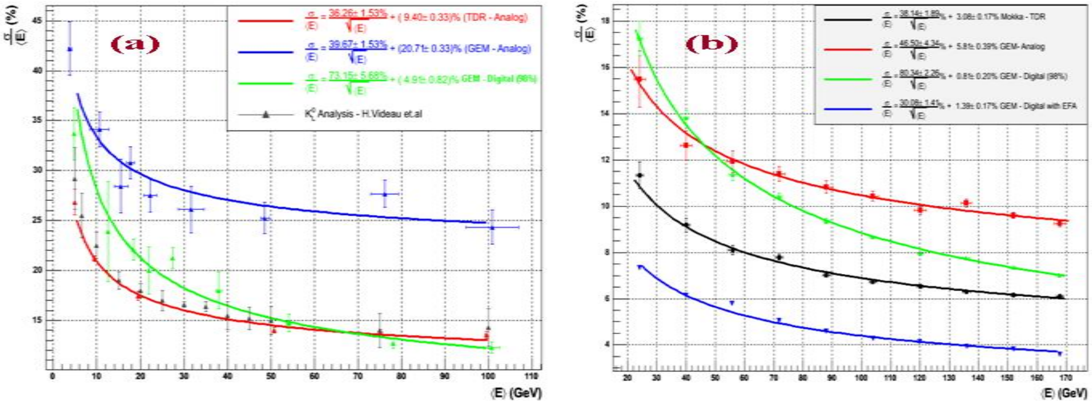

Figure 13. (a) Energy resolution for TESLA TDR (blue), GEM analog (red), GEM digital (green) modes and other detectors (triangles). (b) Jet energy resolutions using various detector techniques. Blue line represents GEM digital with EFA.

As shown in Fig. 13.b, EFA based jet energy resolution using GEM DHCAL (blue line) demonstrates the best resolution with the sampling term at around 30% which is consistent with the expectation.

3.4 Energy Flow Algorithm Development

Improvement in jet energy resolution can be obtained using the energy flow algorithm. For EFA to work, one of the most important procedures is the subtraction of calorimeter energies that correspond to charged tracks whose momenta are measured in the tracking system. Since any algorithm of such subtraction must work very efficiently in simple cases, we have carried out a preliminary EFA studies in two step process. First we determine the best algorithm to identify the centroid of a hadronic shower using single pion events. We explored three distinct methods for centroid determination. The three methods are: (a) Energy weighted method, (b) Simple averaging and (c) Density weighted method. A study shows that while all three methods seem to perform well, density weighted method seems to perform the best for digital methods. We then proceed to two pion shower cases in a GEM based detector in its digital mode using full detector simulation in Mokka through multiple iterations of matching calorimeter and tracker positions to draw the cone of size $\Delta R=0.1$ (half the distance between any two particles).

4. Proposed Plan of work

4.1 30cm x 30cm multi-channel prototype

As the first step toward large scale GEM detector development, we will construct a stack of five double-GEM 30cm x 30cm detectors. We plan on using three of the 32-channel Fermilab preamp cards, already used for our earlier prototype, as the front-end readout. We will read out a central area of 96 channels per detector, as shown in Fig.14.

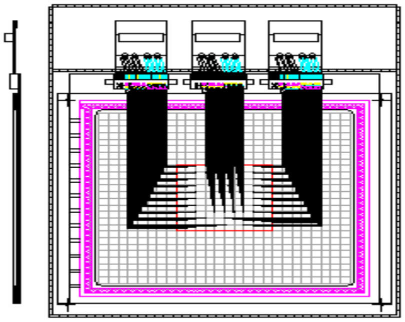

Figure 14. Schematic of anode layer and front end electronics for the multi-channel prototype.

4.2 Discriminator and DAQ system for five double-GEM stack

As reported above, we have been using 32 channel Fermilab QPA02 ASIC card to test prototype double GEM detectors at UTA for some time. Total of 15 cards are needed to readout the 500 channels of the cosmic ray stack and will be mounted directly on to each layer of the stack. Fermilab has agreed to assemble enough cards for us using the existing QPA02 chips. We expect the cost of making such cards will be small. 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 will be readout by a DAQ card in a PC controlled by LabView. The discriminator boards and DAQ system will be developed at the University of Washington.

4.3 Studies with five layer double-GEM stack

The stack will be used to examine the following items: single cosmic tracks hit patterns, hit multiplicity (vs. simulation), signal sharing between pads (e.g. vs. angle), efficiencies of single DGEM counters, effects of layer separators, operational experience with ~500 channel system, as a possible test-bed for ASIC when available (rebuilding one or more DGEM chambers).

4.4 Test beam module development, construction, and testing

The principal task for the next three years will be the construction and testing of a full size (1m^3) GEM-based digital hadron calorimeter stack with a total of 40 longitudinal layers. This is an essential step in the development of linear collider detector technology, in order to (a) demonstrate the viability of this technique (in parallel with the scintillator and RPC-based approaches), and (b) make critical, energy density measurements with fine granularity (~1cm x 1cm), to tune GEANT4 as a reliable tool for EFA development. The testbeam stack will be built at UTA using the 1m x 30cm GEM foils. There will thus be 3 double-GEM panels for each of the forty 1m x 1m layers.

The 1m^3 beam test module, if fully instrumented, requires approximately 400,000 readout channels assuming 1cm ×1cm readout pads. The Fermilab-PPD electronics group is developing a 64 channel ASIC, Fig.15, that has an adjustable amplifier gain and can be used to readout both RPCs and GEM detector planes. This ASIC will receive signals from readout pads, discriminate signals, and tag hits in time to facilitate shower reconstruction. It also has a serial I/O control, serial data output line and a trigger output as shown in the block diagram below. Each ASIC can readout a 8 x 8 detector pad array. We currently envisage that we will have 6 large multilayer printed circuit boards to readout a 1m^2 detector plane as shown in Fig.16. Each board will host 24 ASIC chips.

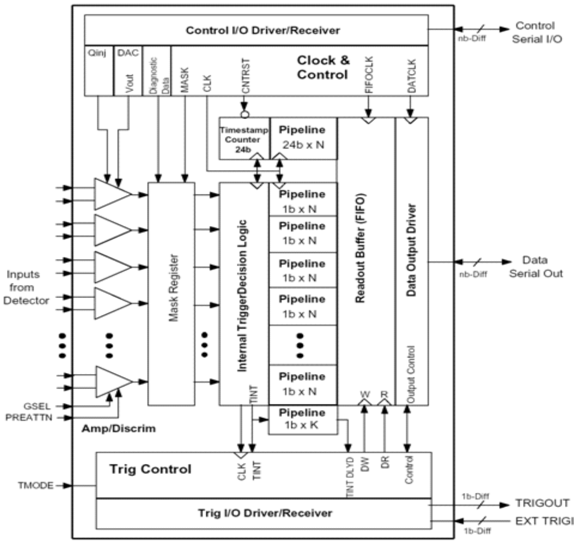

Figure 15. ASIC layout.

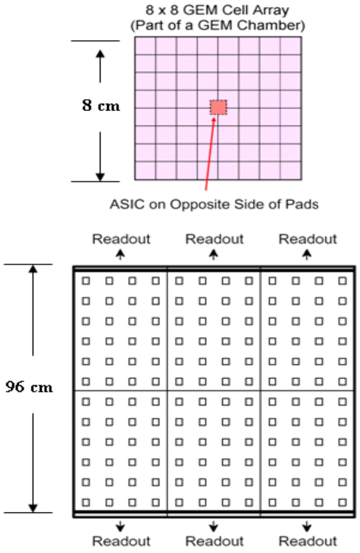

Figure 16. ASIC locations on 1m x 1m plane.

We will start evaluating the ASIC design once the prototype chips become available (expected in late 2005). We will develop a front-end readout board design for the 30 cm x 30 cm double GEM cosmic ray chambers that we will construct in FY2005. This board requires 16 ASICs. When the GEM foil of final size (32 cm x 96 cm) becomes available in FY2006, we will extend the board size to 48 cm x 32 cm and design a readout system for the 1 m x 1 m plane of the 1 m^3 beam test module. It will require 6 boards to readout a detector plane as shown in bottom of figure 16. We expect that the design of these front-end readout boards will be somewhat different for GEM and RPC in some mechanical aspects. The work for prototype ASIC chip testing and the front-end readout board development will be shared between UTA and UW. We will coordinate our effort for developing front-end boards for GEM with the RPC group at Argonne.

For the beam test module, the output signals from the front-end boards will first be processed by the data concentrator boards and then sent to VME cards. These stages of the readout system will be identical for GEM and RPC. The funding for the test beam stack and associated electronics is currently the subject of a NSF-MRI proposal.

4.5 Determination of Detector Parameters.

A study in detector granularity for GEM detector will be conducted to determine cell sizes that can be accommodated without compromising EFA performance of the detector. This will also be the same for other parameters, such as absorber thickness, sensitive gap size, on-board readout electronics sizes, and mechanical support structures. This will be carried out as part of the recently initiated LC detector initiatives in both the silicon detector (Si-Detector) and the Large Detector concepts.

4.6 Continuation of Energy Flow Algorithm Development

The current level of EFA development is very rudimentary since the clustering algorithms for associating the track with the corresponding shower is simply a cone drawn around the centroid of the shower [7]. Given the erratic behavior of hadron showers, the algorithm should be more flexible in its areas of subtraction of shower energies. We will work closely with Argonne National Laboratory and other groups in EFA development. Once a reasonably performing algorithm has been developed, we will move on to a multi-jet environment to test performance of the algorithm.

4.7 Implementation of Cosmic Ray Stack Geometry

Since the hardware development effort will move onto constructing a 30cm x 30cm five layer cosmic-ray stack and taking data, it is necessary to have software and simulation evolve to support this activity. In order to compare the performance of the cosmic-ray stack with expectations from simulation, the new geometry needs to be implemented in the simulation package. In addition, cosmic-ray data analysis software must also be developed. The data from the cosmic-ray stack and the simulation can then be used for development of tracking algorithms through the calorimeter. These studies will need to be done in both analog and digital modes to compare performances.

4.8 Implementation of Testbeam Stack Geometry and Software Development

We expect to participate in a testbeam experiment [8] on the 2006 – 2007 time scale, contingent upon availability of funds. The geometry for testbeam experiment must be implemented and the corresponding software for reconstruction and analysis must be developed ahead of the actual data taking. Currently, Northern Illinois University has developed a testbeam simulation package. We plan to exploit the existing package and implement our GEM geometry into the system for the initial studies in the testbeam stack. Studies will also have to be conducted to determine particle types, energy range and statistics for adequate precision for the testbeam needs.

4.9 Discharge Study

One of the fundamental properties of the GEM detector we need to understand is the discharge probability in a given GEM gap, which might damage the GEM foil, thereby disabling the affected area. In addition, the possibility of low energy ionization electrons spiraling through the gas gap due to the configuration of electric and magnetic fields, causing large signals needs to be looked into to determine the method to prevent or minimize this effect, if present. For this study, a new simulation program Garfield [9] is being implemented for this study since the current GEANT based simulation program we use, Mokka, does not allow this level of detailed studies.

4.10 World-wide Linear Collider Test Beam Coordination

Yu has been asked to lead the American Linear Collider Test Beam working group. He has taken initiatives in putting together a report [10] on current World-wide LC testbeam effort and a planning document [8]. This report has been completed recently and been released to the World-wide LC community. This testbeam effort should continue in the next 2 – 4 years to help determine technological choices and the conceptual and technical design reports on both the LC detector initiatives.

5.0 Timeline for proposed work

FY05 - 30cm x 30cm detector stack
- Develop test 1m x 30cm foils
- Prototype run of ASIC and its testing
- NSF- MRI → start of 1m^3 test beam GEM module development and construction
- GEM, SPICE, Garfield and Test Beam simulations

FY06 - Completion of 1m^3 test beam GEM module
- Begin program of GEM/RPC beam tests
- Further EFA development

FY07 - Further beam tests, data analysis, GEM-DHCAL calorimeter system design

6.0 Facilities, Equipment, and Computing Resources

The UTA HEP group has a 10,000 ft^2 detector construction facility, an excellent mechanical workshop, and a very high performance parallel computing farm. In late 2005 these facilities will be integrated as part of a new $40M Physics and Chemistry Research building.

7.0 Budget and Discussion The budget request is given in the table below.

Personnel We request support for a post-doctoral associate for six months, for each of the three years. The UTA postdoctoral fellow supported will be Dr. Jia Li who has been working on our GEM prototypes, drawer assembly techniques, and calorimeter module design. We also request support for two months of engineering support in FY05 at UW for electronics design and development for the cosmic stack. We request support for a graduate student in FY06-07 to work on the testbeam stack, and analysis of data from the testbeam.

ITEM	FY05	FY06	FY07
0.5 Postdoc	21000	22050	23152.5
Fringe	6300	6615	6945.75
Engineer (2 months)	11500		
Fringe	3450		
Graduate student		21600	22680
Fringe		9720	10206
Cosmic Ray Teststand	10,000		
Discriminator Boards	6,000		
Travel	8000	8000	8000
Materials and Supplies	10000	5000	5000
Direct costs	76250	72985	75984.25
Indirect costs	28920	35032.8	36472.44
TOTAL	105170	108017.8	112456.7

Equipment We request support to construct the cosmic ray test stand to be used with the stack of five 30cm x 30cm double-GEM chambers. We also request support for the discriminator boards for the same setup to be developed at UW.

Travel For each year we request a limited amount of travel support to attend Linear Collider Workshops and meetings, during this development phase for the Linear Collider Detector. We also request support for one foreign trip each year to attend the LCWS conference or meeting(s) of the CALICE collaboration [11], of which UTA is a member. We have specific responsibilities that involve travel as follows: (1) Andrew White is the U.S. CALICE Steering Board representative, and (2) Jae Yu is the chairperson of the CALICE Technical Board, and the ALCPG testbeam coordinator.

9.0 Broader Impact

This project has already had an impact in a number of areas. Two graduate students have obtained MS degrees with the studies on GEM detector performances and EFA development using simulated data. Currently, four undergraduate students are working on prototype development and simulations.

Andrew White and a UTA condensed matter colleague have developed a high resolution Positron Emission Tomography system using GEM foils that is the subject of a patent application. We are also discussing the possible applications of GEM foils in very large area radiation detectors for homeland security applications.

UTA has an active Quarknet educational program that has evolved into an expanding program of installing cosmic ray detectors in local high schools. We are currently using scintillation counters, but anticipate having students work with GEM foils once they are made for our project in larger quantities. The students we are working with are drawn from the Hispanic population of Fort Worth, Texas in an effort to increase the number of such students pursuing careers in science.

10.0 References

1. F. Sauli, Nucl. Inst. Meth., **A386**, 531 (1997).
2. ALEPH Collaboration, Nucl. Inst. Meth. **A360**, 481 (1995);
3. Mokka Home Page, http://polype.in2p3.fr/geant4/tesla/www/mokka/mokka.html
4. GEANT4, detector simulation toolkit, http://geant4.web.cern.ch/geant4/
5. F. Richard, *et al.*, TeV Energy Superconducting Linear Accelerator (TESLA) Technical Design Report, (2001); http://tesla.desy.de/new_pages/TDR_CD/start.html
6. S. Habib, “Simulation Studies of a New Digital Hadron Calorimeter, Using Gas Electron Multipliers (GEM)", MS Thesis, University of Texas at Arlington, UTA-HEP/LC-003, Unpublished (2003).
7. V. Kaushik, “Performance of Novel Digital Hadron Calorimeter Using Gas Electron Multiplier (GEM) and the Energy Flow Algorithm Development,” MS Thesis, University of Texas at Arlington, UTA-HEP/LC-004, Unpublished (2004).
8. J. C. Brient, J. Yu *et al.*, World-wide Linear Collider Test Beam Working Group, “International Linear Collider Calorimeter Test Beam Program (A Planning Document for Use of Test Beam Facility at Fermilab,” FNAL-TM-2291, In preparation (2005).
9. R. Veenhof, Simulation of gaseous detectors, http://consult.cern.ch/writeup/garfield/
10. Linear Collider Test Beam Working Group, http://www-lc.fnal.gov/lc_testbeams/wwlctb_working_group.pdf (2004)
11. CALICE Collaboration, http://polywww.in2p3.fr/flc/calice.html