Calorimetry R&D at Colorado
Progress Report of Work in 2004
and Proposed Work for 2005,2006,2007

Paul Beckingham, Shenjian Chen, Keith Drake,
Eric Erdos, Jason Gray, Jack Gill, Andrew Hahn, Keith Miller,
Uriel Nauenberg (Project Leader), Martin Nagel, Matthew Phillips,
Joseph Proulx, Hang(Jerry) Qi, William Ruddick,
Jesse Smock, Steven Wagner, Jinlong Zhang

January 17, 2005

Overview

The colorado group is actively engaged in the design of a scintillator based electromagnetic/hadronic calorimeter where alternate layers of scintillator tiles are displaced relative to one another by half a tile width in order to improve the spatial resolution while maintaining the excellent energy resolution. Funding wise we receive a yearly DOE grant. This year the grant is $291K. In addition I received last year an LCR&D grant of $60K. We discuss here the effort that has been carried out in our group during 2004 and the work we propose to carry out in the next three years, 2005-2007. All the results discussed in the progress aspects of this report can be found at `http://hep-www.colorado.edu/SUSY`.

The resolution of the calorimeter we are proposing is such that it is tailored to be used with the large gaseous trackers like the US Large Detector, the Tesla Detector proposed by Europe or the GLD detector proposed by Japan. The design we are proposing here can easily we incorporated into a hadronic calorimeter for any of the detectors being proposed including the Silicon version. We itemize the topics in which we have been active and discuss them in more detail later on:

- **SUSY Signal Simulation**This work, being carried out mainly by undergraduates students supported by University funds through the Undergraduate Research Opportunities Program (UROP), and including high school students was started about eight years ago and is continuiing. About fifty undergraduate and ten high school students have worked in this activity during this period of time. This has provided an avenue for the students to become very well educated in various research techniques like software simulation, least square fits, error propagation, development of cuts to remove background, etc. They have learned how to use various event generation packages like ISAJET, PHYTHIA, etc. Some have learned GEANT. You can see their work over the years in the web address stated above. We have developed a more general method to determine the masses of the Supersymmetric particles which does not depend entirely on the energy end point method introduced by our Japanese colleagues [1]. We will not discuss any of this activity in great detail since it is not directly related to the calorimeter design.
- **Detector Simulation.** We have simulated γs and π^0s in our electromagnetic calorimeter design with various tungsten and scintillator thicknesses and number of layers to determine their various resolutions. We propose, using the resolutions we obtained together with the charged particle tracker resolutions and possible hadronic calorimeter resolutions, to determine how these various resolutions affects the Z and W mass measurement widths in order to optimize the design. This work is being carried out by the undergraduates in our group under the guidance of Jason Gray with the help of Steven Wagner and should be finished in 2006. Steven Wagner was a senior staff member at SLAC who is now an Adjoint Associate Professor at Colorado.
- **Pattern Recognition.** We are beginning a computer effort to do pattern recognition on electromagnetic showers to determine how we can separate single from double photon showers where the photons come from π^0s and determine how our pattern recognition limitations affect the resolution. This work will be a multi-year effort involving the more senior members of our group, including one undergraduate. It will probably carry us through 2006.
- **Electronics.** Paul Beckingham, the electronics engineer in the Joint Institute for Laboratory Astrophysics, is working with us. He is designing the electronics associated with the Silicon Photo Sensor that we are planning to use with each scintillator tile in our Electromagnetic Calorimeter Design. We discuss this program in reasonable detail and will require a multi-year effort probably ending in 2007.
- **Study of Scintillator Elements.** We have studied the light output from scintillator tiles with reflecting Tyvek paper and with Radiant Mirror paper to compare the light output. This work is completed.
- **Study of Light Transmission in Scintillating Fibers** We studied the light transmission of scintillating fibers as a function of bending radius. This work is completed. We are making a long term measurement of fibers to determine whether their transmission properties change with time when bent into small radii. This work will probably take us through 2006 or longer.

- **Production of Extruded Scintillator.** We have received some samples of extruded scintillator from Fermilab. We are working with the Fermilab-Northern Illinois University (NIU) extruded scintillator group, in particular Victor Rykalin and Anna Pla-Dalmau, that produce the extruded scintillator to attempt to produce materials of more uniform thickness than achieved so far. This work will continue in 2005 and last through 2006.
- **Mechanical Structural Design.** We have initiated a collaborating effort with the Mechanical Engineering Department in the University of Colorado at Boulder, in particular with Assist. Prof. Hang Jerry Qi, in order to understand how to construct the modules. This will be carried out through a finite element analysis (FEA) technique. This work will be carried out in 2005.
- **Construction of a Module for Test Beams** We propose to build a 50cm x 50 cm by 40/45 layer module in 2006-2007 to insert in a test beam and determine its properties under real conditions. This can not be carried out until we solve the design details in 2005.

0.1 SUSY simulation

We are continuing our studies, started eight years ago, to determine how best to measure the properties of Supersymmetric particles if they are produced in the collisions. We have determined already, because of beamstrahlung and bremmstrahlung degradation of the center of mass energy, that the energy end point method does not provide a correct value of the masses. We have developed a new Chi-Square minimization of the full energy spectrum that takes into accounts these center of mass energy effects and gives the correct results.

All this work is being carried out by a group of undergraduates working in our group and supported mainly by University supported programs. Their work is shown in our web page `http://hep-www.colorado.edu/SUSY`.

We do not describe this work here any further although this work will continue where we now plan to use GEANT to generate the events in the detector and then proceed with the reconstruction and analysis. This will be a more realistic representation of the final supersymmetric particle mass measurement.

0.2 Detector Simulation

We have started a program to understand the resolution of the detectors being proposed. This requires us to understand the resolution of every element of the detector and to separate the activities of every part of the detector.

We have developed the code to propagate the charged tracks into the electromagnetic calorimeter following the magnetic field lines. In this manner we can remove the energy deposition in the tiles due to charged tracks. This is necessary to do a proper reconstruction of the γs from π^0 decays using their electromagnetic showers. In Fig 1 we show how well we can correlate the number of tiles hit by the tracks with the tiles where Geant says energy has been deposited by muons, electrons, hadrons. This work will be improved and will be used to reduce the confusion when we carry out the pattern recognition of electromagnetic showers to reconstruct π^0s. This code was developed by Jason Gray, who started working in our group as an undergraduate and is now a graduate student with us.

We have started a program to understand the needed resolution of our scintillator based electromagnetic calorimeter design with offset layers. Our design consists of 5cm x 5 cm tiles where alternate layers are offset to make the effective areas 2.5cm x 2.5 cm. Using GEANT and reconstructing the associated electromagnetic showers from photons, we have determined the resolution of three widely different versions of this electromagnetic calorimeter design. The variations consist of different radiator and scintillator thicknesses. These are then associated with the resolution of the various tracking chambers and hadronic calorimeters being proposed in order to study the W and Z signals when they decay into hadronic modes. The three electromagnetic calorimeter versions being simulated are:

- 60 layers made up of 1.75mm of Tungsten(1/2 X_0),2.00mm of Scintillator surrounded by 100μ of Radiant mirror paper, and 1mm of empty space. The effective energy and spatial resolutions are shown in Figure 2.

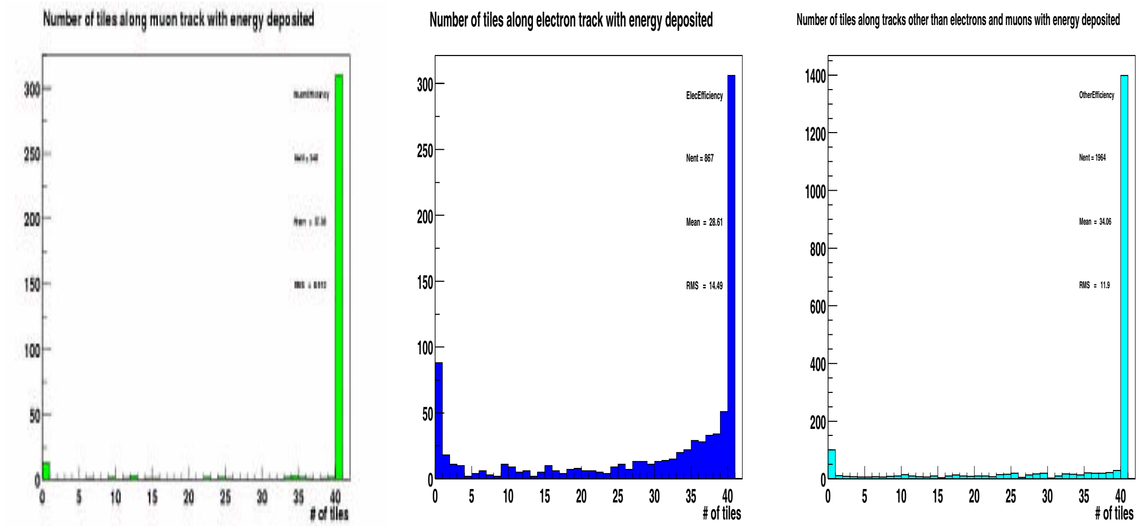

Figure 1: The number of correct tiles hit by muons (left), electrons (center), hadrons(right) propagated into the electromagnetic calorimeter using the track generated in the tracking chamber. As can be seen our track following algorithm is quite efficient except in the case of electrons. In the case of hadrons, the tail observed is due to hadrons interacting in the lectromagnetic calorimeter and the tracking algorithm failing to take this into account.

- 40 layers made up of 2.62mm of Tungsten(3/4 X_0),3.00mm of Scintillator surrounded by 100μ of Radiant mirror paper, and 1mm of empty space. The effective energy and spatial resolutions are shown in Figure 3.
- 40 layers made up of 3.50mm of Tungsten(1 X_0), 3.00mm of Scintillator surrounded by 100μ of Radiant mirror paper, and 1 mm of empty space. The effective energy and spatial resolutions are shown in Figure 4.

Using a parametric function describing the various resolutions we will study, during the next year, how well we can separate the W and Z signals using the TPC tracker of the US and European Large detector, of the GLC detector designed by our Asian colleagues and using the silicon tracker of the American Silicon based detector. This work is being spearheaded by Jason Gray with three undergraduates under his direction. Steven Wagner will work with our group to help understand how to use the tracking Fast MC smearing routines.He will work with Jason Gray and Joseph Proulx. This work will be a main effort in 2005 but may well continue into 2006.

0.3 Pattern Recognition

We have a program to determine the photons energy and direction when they come from π^0 decays. Our preliminary results are shown in Figures 5,6,7,8. The student doing this work graduated last summer; hence we have to continue this work with other students and this has stopped our progress. We have now reinitiated this effort and it will continue through 2006. We will reconstruct these photons in the middle of a Z or W hadronic decay to determine how well we can reconstruct the π^0s and ultimately the W and Z.

This result needs to be viewed in the context that in a 500 GeV Z or W hadronic decay only a few % of the π^0s have energies above 50 GeV. Most of them are 20 GeV or less.

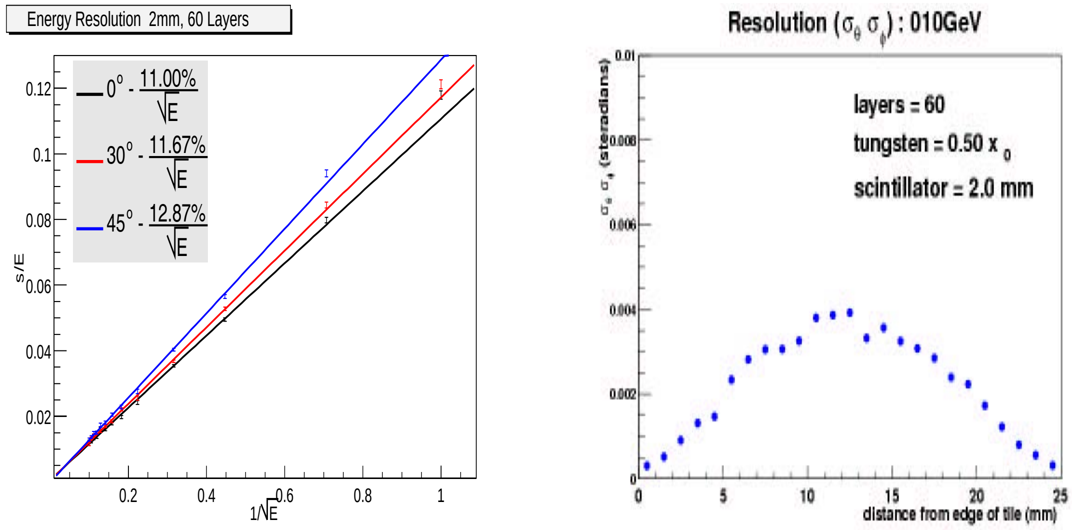

Figure 2: The energy(left) and angular resolutions (right) for the electromagnetic calorimeter made up of 1/2 X_0 Tungsten and 2 mm Scintillator.

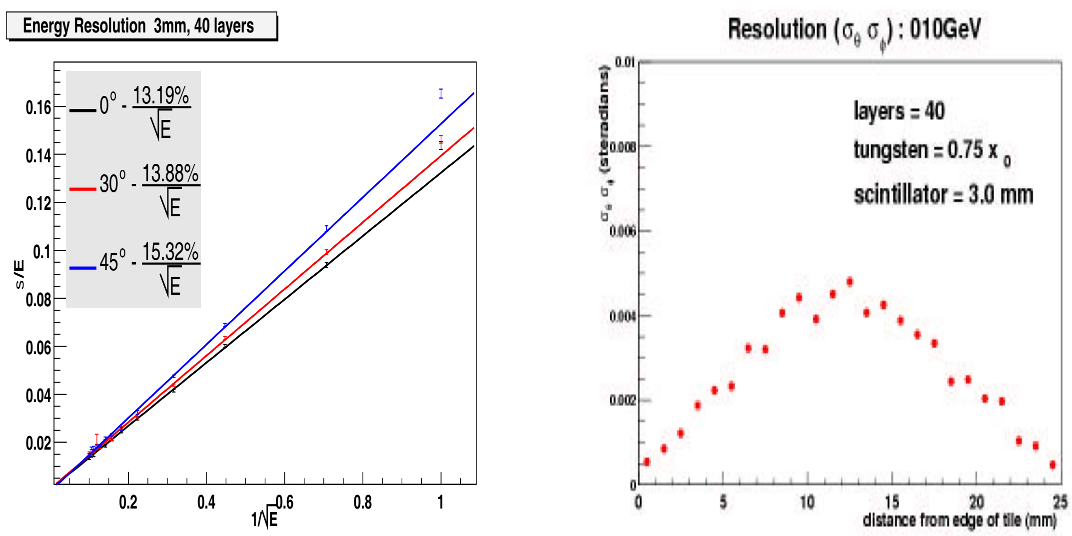

Figure 3: The energy(left) and angular resolutions (right) for the electromagnetic calorimeter made up of 3/4 X_0 Tungsten and 3 mm Scintillator.

0.4 Electronics

We have received a few Silicon Photo Sensors from Russia and an electronic readout schematic with the help from Felix Sefkow from DESY. We have developed the electronic readout further in collaboration with Paul Beckingham, the electronics engineer in the Joint Institute for Laboratory Astrophysics (JILA) at the University of Colorado, Boulder.

We have received as a loan a device just produced by Multi Channel Systems (MCS) [2] that replicates very closely

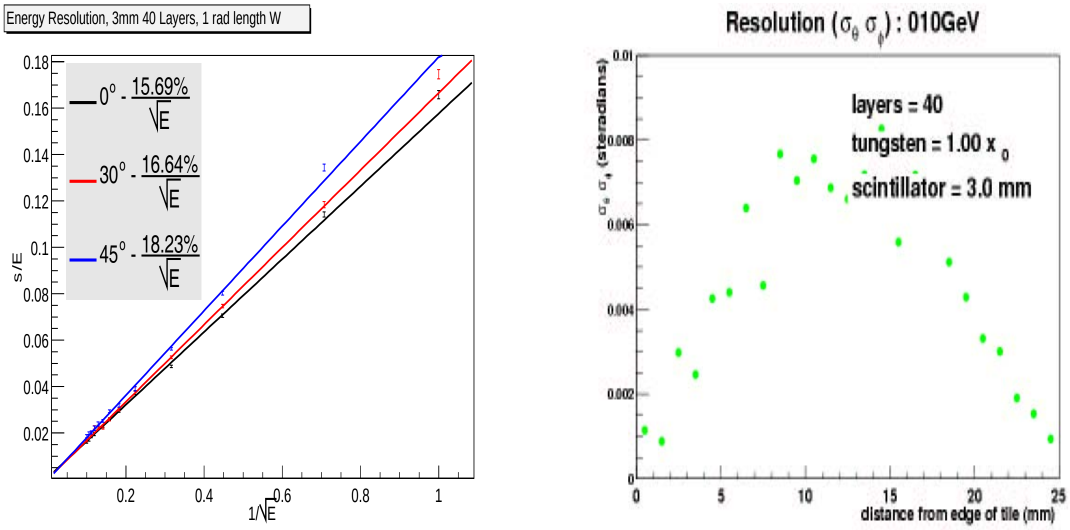

Figure 4: The energy(left) and angular resolutions (right) for the electromagnetic calorimeter made up of 1 X_0 Tungsten and 3 mm Scintillator.

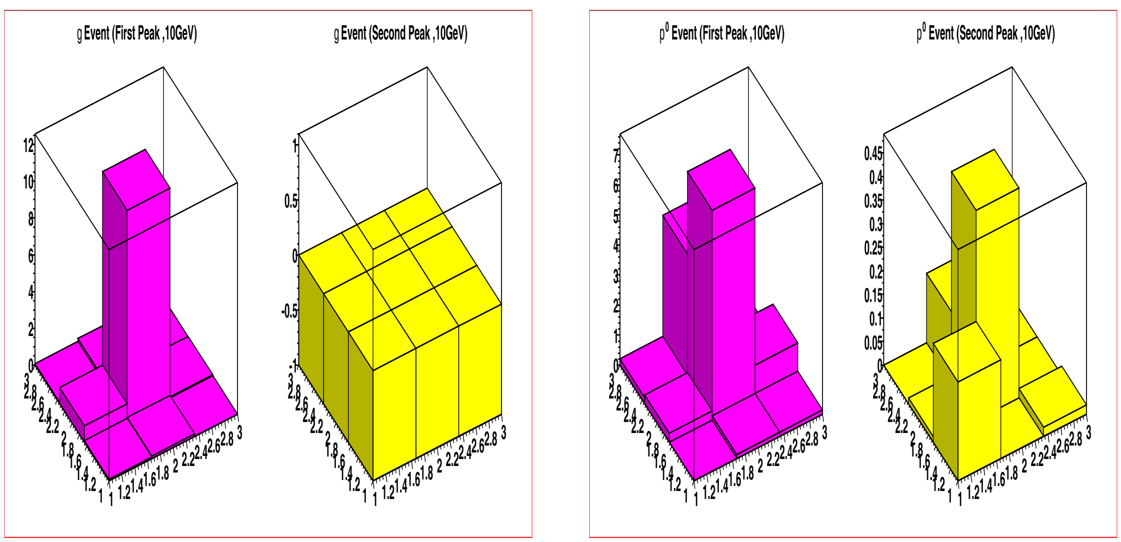

Figure 5: These figures show how the energy distribution of a single 10 GeV γ is different from the energy distribution of the 2 γs from a 10 GeV π^0. In almost all cases our calorimeter array can detect the 2 γs.

the desired electronics circuit that provides the integral of the pulse which represents the energy being deposited in the scintillator tile. See Fig 9. These devices have a 2-gain range depending on the magnitude of the input pulse. We are starting a collaboration with this company to determine whether this circuit can readout accurately the pulse height from the Silicon Photo Sensors over our desired dynamic range. We have already determined that the device gives outputs with two different gain ranges depending on the integral of the input pulse in the voltage range associated with our calorimeter and that the height of the output pulse is correlated with the integral of the input pulse. Our preliminary measurements carried out over the last month shows that the module has a dynamic range

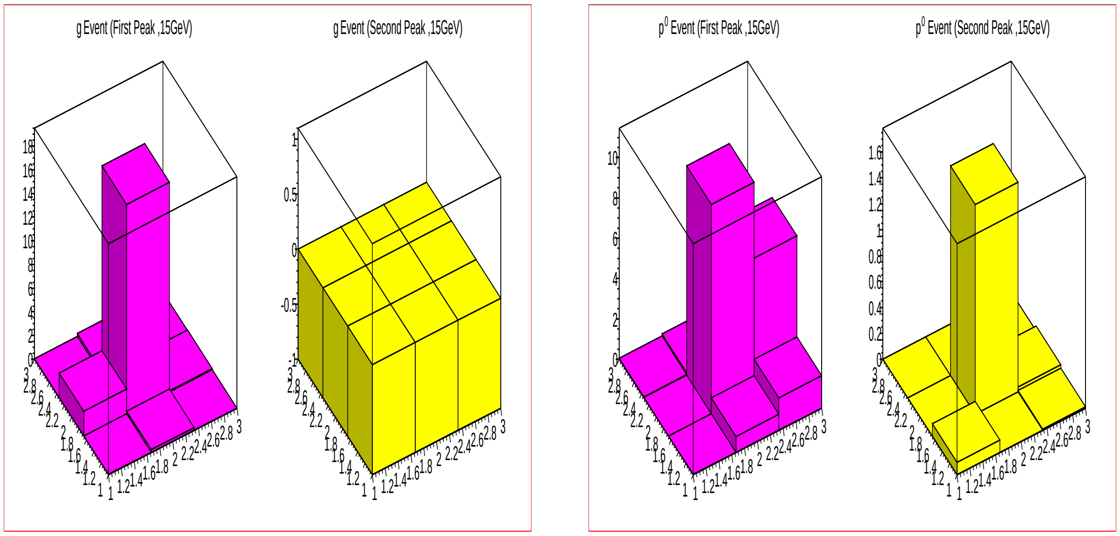

Figure 6: These figures show how the energy distribution of a single 15 GeV γ is different from the energy distribution of the 2 γs from a 15 GeV π^0. In almost all cases our calorimeter array can detect the 2 γs.

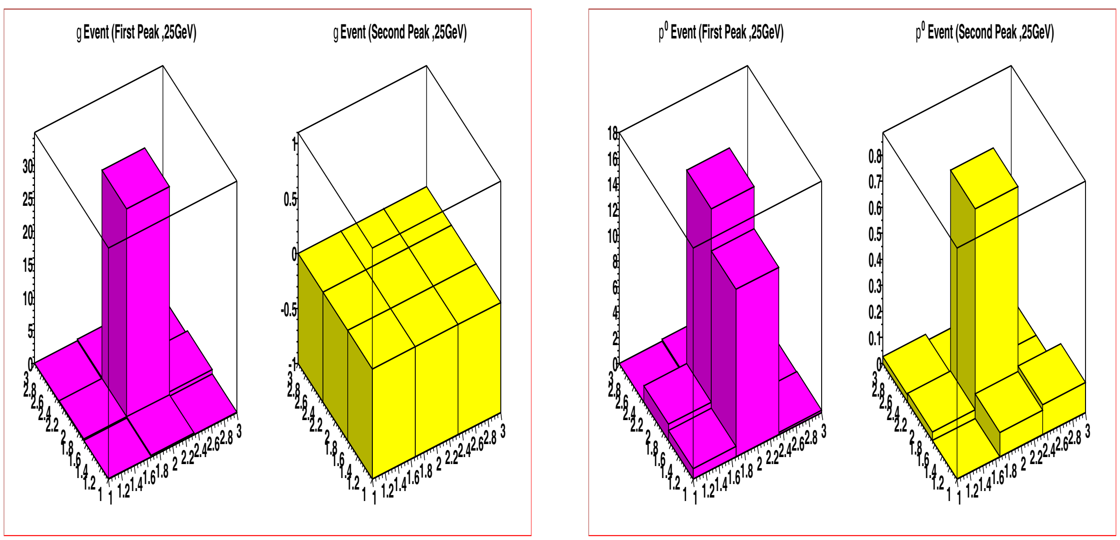

Figure 7: These figures show how the energy distribution of a single 25 GeV γ is different from the energy distribution of the 2 γs from a 25 GeV π^0. In about 75% of the cases our calorimeter array can detect the 2 γs.

of 5000 which is quite encouraging. We propose to continue this work. Starting in January, 2005 we will begin to read out these devices using a light emitting photo diode as a light source. Our effort will be to determine the linearity and the timing characteristics associated with these devices. The module developers are improving their 2-gain range quality to meet our requirements. They are also actively designing a modification to their module to provide a fast timing output. If such a 2-gain plus fast timing pulse module can be developed by MCS, then we will have the needed electronics to read out a single channel Silicon Photo Sensor in a 1in x 2in module.

At the same time we have begun the design integrating the module provided by MCS but presently without the

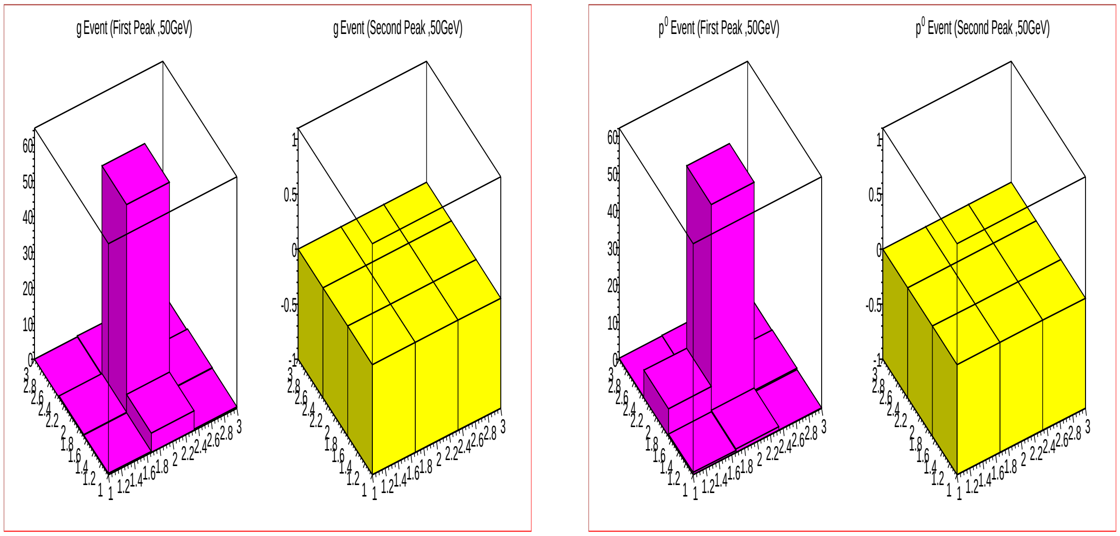

Figure 8: These figures show how the energy distribution of a single 50 GeV γ is different from the energy distribution of the 2 γs from a 50 GeV π^0. For this particular example we can not observe the 2nd γ. In about 40% of the cases our calorimeter array can detector the 2 γs.

fast timing signal. This is shown in Figure 10.

If we are successful during our early 2005 measurements to determine that these modules can be used then we will be able to specify more exactly the various gains and time constants desired for our exact application. If MCS can provide a prototype that meets our requirements to our satisfaction then we propose to integrate 100 of these modules into a prototype assembly. This would accept pulses from 100 Silicon Photo Detectors, create low and high gain range pulse integral outputs as well as a fast timing pulse for every channel. We will then design the additional hardware to send the data to a computer for analysis. The prototype instrument will also provide the 50v bias for the Silicon Photo Sensors and the $\pm$ 5v adequate for the 100 modules.

We expect, if successfull by the middle of 2005, to be in a position to work with MCS to provide us a large number of these modules at a competitive price. They are only a relatively small firm and are interested in collaborating with us to provide a large number of modules, either by producing them directly or by allowing us to organize the production through a licensing agreement. We can then begin to organize the production and testing of a large number of modules. We can expect this work to cover the period of 2005. If successful we propose to order 2,300 of these in 2006 and 2,300 in 2007 to install into our 50cm x 50cm test calorimeter, 100 tiles per layer and 45 layers, to place in a test beam.

0.5 Study of Scintillator Elements

We studied the relative light observed from scintillator tiles when covered with Tyvek paper [3] and with Radiant Mirror paper [4]. This was done using cosmic rays. The results, as shown in Figure 11, indicate that Radiant Mirror gives us 20% more signal than Tyvek covering the same scintillator tile. This work is now completed and we will use Radiant Mirror paper to provide the cover to our scintillator tiles. The work is discussed in `http://hep-www.colorado.edu/SUSY/grp_meas.html`; it was carried out by graduate student Martin Nagel in collaboration with undergraduates Jesse Smock and Keith Drake.

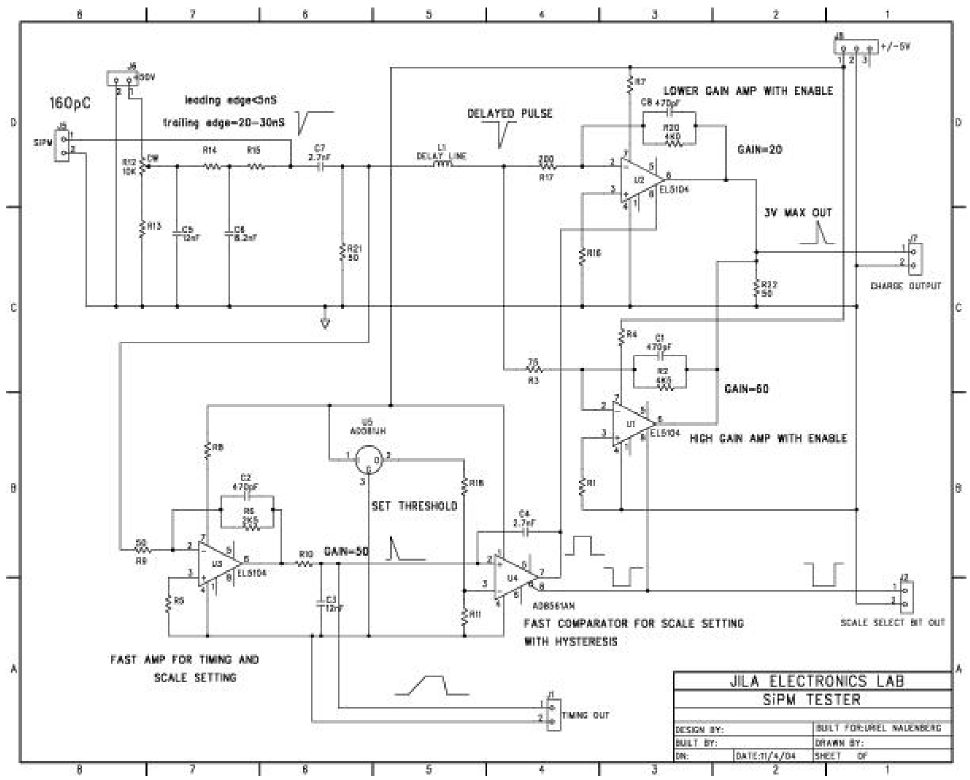

Figure 9: Schematic of electronics to readout the Silicon Photo Sensors as designed by Paul Beckingham.

0.6 Study of Light Transmission in Scintillating Fibers

We measured the relative light tranmission in green shifting scintillating fibers when the fiber was bent in a circle of radius 8, 6, 4 ,2 cm. We used a light emitting diode as the ligth source. The results for 2 and 8 cm are shown in Figure 12. The same signal amplitude was seen for the case of 4 and 6 cm. This work is discussed in `http://hep-www.colorado.edu/SUSY/grp_meas.html` and is completed. This work was carried out by Martin Nagel and collaborators.

We have begun a long time scale measurement of the light transmission of these fibers over the period of a year to determine whether the fiber bent in the 2 cm radius structure deteriorates on this time scale. We do this by comparing the light transmission of the fibers in the 8 cm radius and the 2 cm radius as a function of time and determine whether any differences appear. This work is being carried out by Martin Nagel and collaborators.

0.7 Production of Extruded Scintillator

We have measured the thickness uniformity of extruded scintillator produced by the Fermilab- NIU group. We have observed variations of .07 mm in 5 mm thick pieces, mainly near the edges. We have begun a program, in collaboration with the NIU-Fermilab group, to produce 2 or 3 mm thick pieces with variations in thickness no larger than .03 mm. and variations in width no larger than 1 mm in 15 cm wide pieces. The measurements we have carried out so far are recorded in `http://hep-www.colorado.edu/SUSY/grp_meas.html`. To carry out this work we likely will need to build a new molding unit; this would be built by the NIU-Fermilab group. This effort will be carried out during the year 2005. Eric Erdos is working on this with Keith Drake.

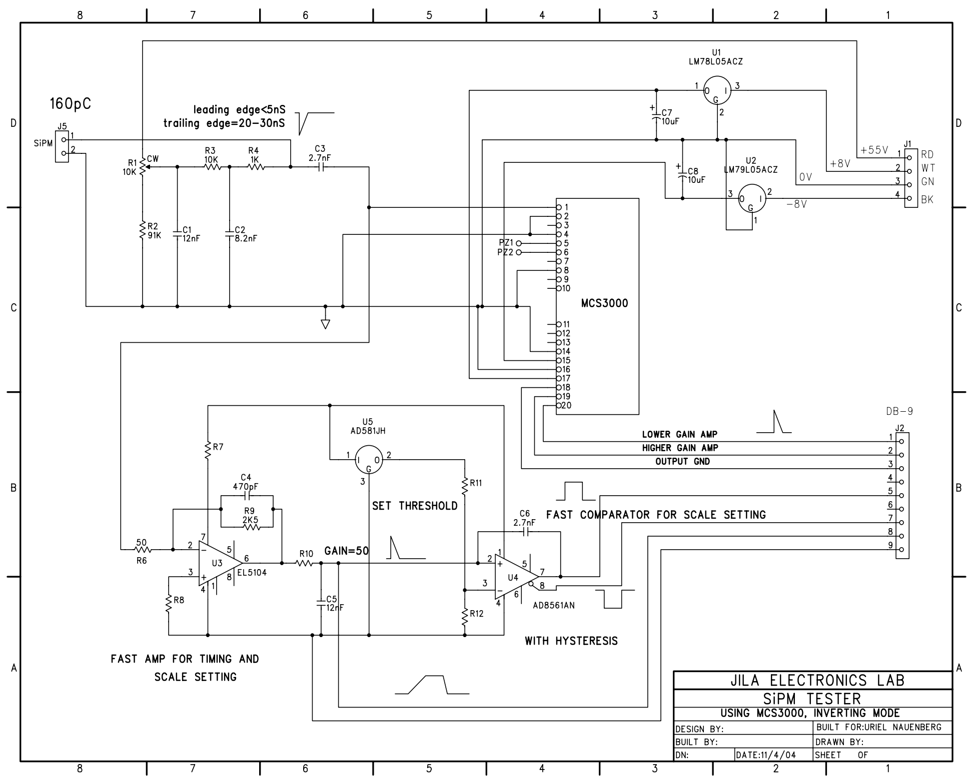

Figure 10: Schematic of integrated electronics readout with the MCS module.

0.8 Mechanical Structural Design

This work, to be carried out in 2005, consists of two efforts. First, Tungsten plates as produced presently in industry are not larger than 100cm x 25 cm with a thickness as we request between 1.75 and 2.62 mm. The width of the large detector electromagnetic modules vary from about 160 cm to 200 cm. This implies that we need to learn how join 2 pieces while maintaining the required flatness. It is typical in industry to use a braising process to join two pieces. At present, it is not clear whether this process will maintain the required flatness of the joined pieces. We are proposing to carry out this test with the aid of industry. If this does not work we propose to investigate a process of laminating two such pieces with thin stainless steel plates and using rivets to provide the stiffness necessary to maintain the flatness required by our electromagnetic calorimeter. Eric Erdos is carrying out this work.

Second, Prof. H. Jerry Qi, from the University of Colorado Mechanical Engineering Department, has joined our effort to help with the Structural Study of the Electromagnetic Calorimeter Modules. Initially he will help us, by means of computer simulations using Finite Element Analysis (FEA), to determine whether our proposed method of joining the Tungsten pieces using rivets will maintain the necessary flatness over a width of 160 to 200 cm. Then he will also help with the design of the construction of the modules. The proposed structure consisting of eight modules forming an octogon with the beam line as an axis is shown in Figure 13. Each module is about 34cm thick, 160-200 cm wide and 320 cm long on each side of the interaction point ending up with a total of 16 such modules. Each module consists of about 40 layers, each consisting of a mixture of 3mm extruded scintillator, .15 mm of Radian Mirror reflecting paper on each side, 1 mm of free space and 2.62 mm of Tungsten as shown in Figure 14. The net weight of each module is $\approx$ 12 metric tons. The extruded scintillator consists of 5cm x 5cm tiles with wave shifted scintillating fibers that go to a Silicon Photo Detector imbedded in the scintillator as shown in Fig 14. Wires leading

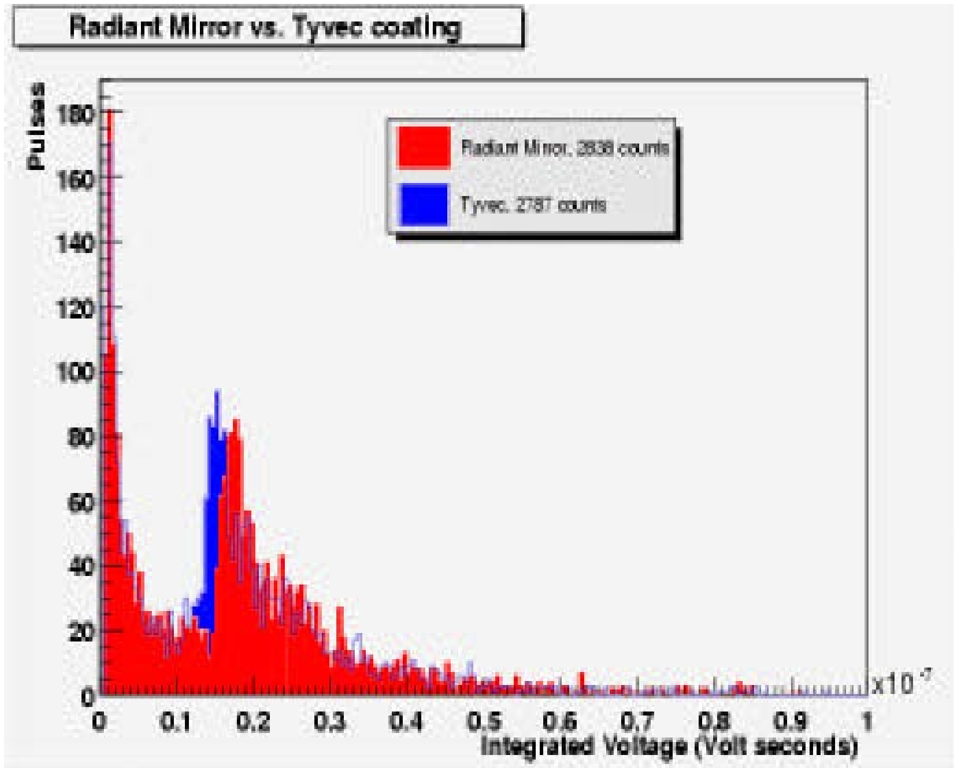

Figure 11: The observed signal from 2mm thick scintillator tiles covered with Tyvek and with Radiant Mirror. The signal from the tile when covered with Radiant Mirror (red) is 20%larger than when the tile is covered with Tyvek (white).

from the Silicon Photo Detector through the 1 mm free space go to the electronics located on the edge of the detector.

Properly designing and integrating these elements into a detector with proper mechanical stiffness to ensure overall flatness of the detector is critical to the success of the proposed calorimeter. In addition, the procedures for assembling the detectors into the final structure and the mechanism to ensure integral accurate parallelism with respect to the beam line is also crucial to the success of the detector. Neither the scintillator nor the wires from the scintillator to the outside can feel any pressure from the Tungsten plates. Hence, during 2005, we propose to carry out two finite element analysis:

- **Analysis 1**Design a module detector with proper loading carrying mechanism so that the first few layers of the electromagnetic calorimeter are protected given the self weight of the module and to ensure that the deflections can meet the stiffness requirements. The major challenge in designing the detector comes from the distinct dimensions between the basic elements such as the 5cm x 5cm scintillator tiles, the 1 mm free space, and the length (3.2 m) of each module. Also we estimate each module to weigh 12 metric tons. Such a heavy weight could create a significant deflection of the detector and may crush the scintillator in the first few layers. In order to study how to overcome these challenges we will carry out a FEA. The iterative design methodology of concept-design/FEA-analysis/modifying-design will be employed. In addition, in order to ensure that the proposed design can meet the system requirements, a 50cm x 50cm detector with an initial Al backing followed by four layers of /relector/scintillator/reflector/ space/tungsten will be machined and subjected to mechanical tests. These tests will consist of compression, tension and three point bending. The test results will be compared

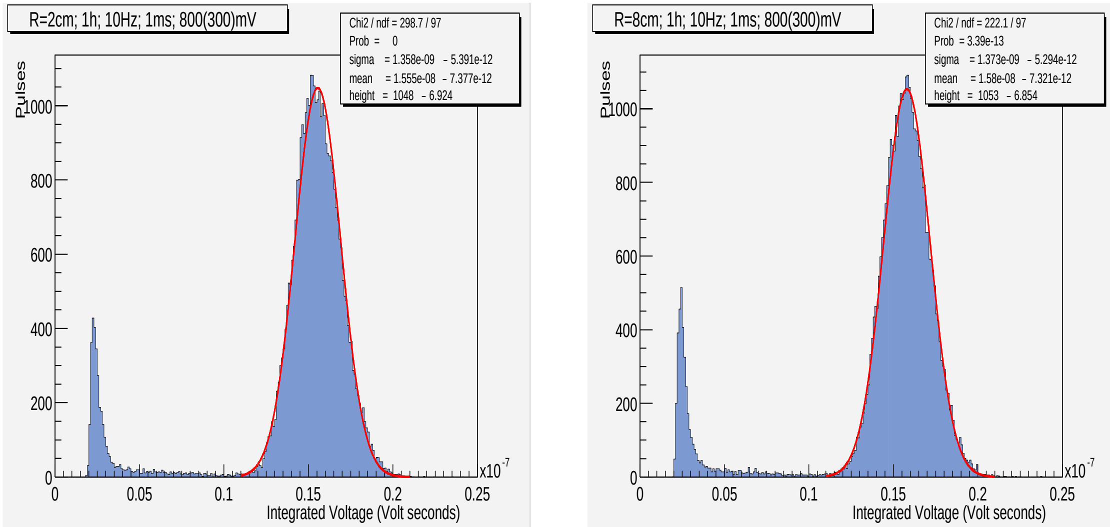

Figure 12: The light transmission observed from a green scintillating bent in a 2 cm radius (left figure) and an 8 cm radius (right figure). We use a light emitting diode as the source. We see little or no difference in the signal observed in the two cases.

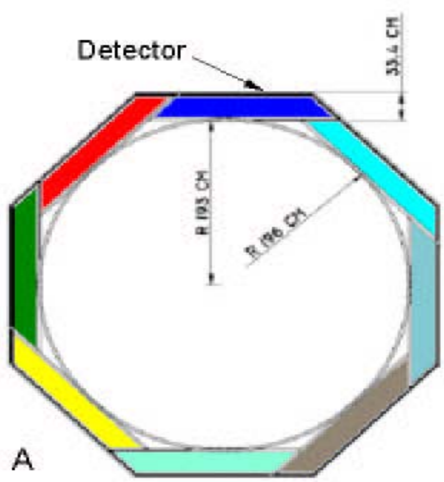

Figure 13: Structure of the octogonal arrangement of the electromagnetic calorimeter on which the FEA analysis will be applied. Each element of the octogon weighs approximately 12 tons.

with the FEA predictions to justify the design and the FEA models, which can the move to the design effort in item 2.

- **Analysis 2**We need to design the connecting and supporting elements that connect the 3.2 meter long modules to form the octogon shown in Figure 13. The proper design of the connecting and supporting elements will ensure the accurate parallelism of the electromagnetic calorimeter relative to the beam line. Several connecting

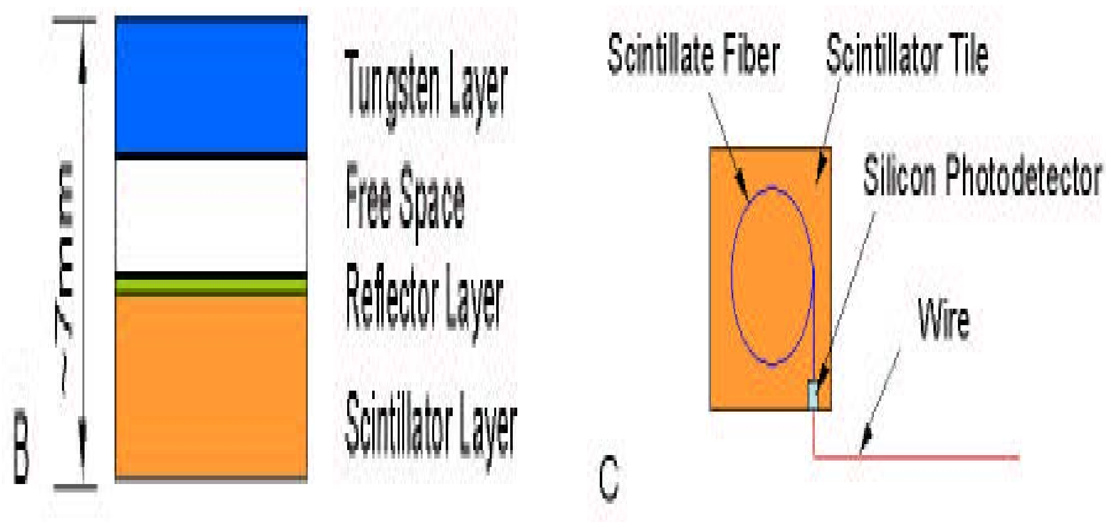

Figure 14: Spatial Structure of every layer and scintillator tile arrangement with silicon photo detector in place. The FEA analysis will take this arrangement into account.

and supporting mechanisms will be designed and analyzed using FEA and the best design will be chosen.

All this computer analysis work we propose to carry out in 2005. We propose that the work in 2006 consists of building a 40/45 layer calorimeter to place in a test beam to justify the resolution results we have determined with our simulations and our electronics development. Hence we propose to be ordering the pieces to produce a 50cm x 50cm by 40/45 layer electromagnetic calorimeter during the three year period 2005-2007. The thickness of the scintillator and tungsten plates will depend on the results we obtain during the first half of 2005.

0.9 The Budget

The main areas of work in the next three years are four:

- To continue with our simulation work to show the effectiveness of our calorimeter design in separating W and Z hadronic decays. This work will continue to be carried out by a graduate student and undergraduates supported mainly by University funds. We are requesting funds for the one graduate student, Jason Gray.
- To carry out the development of the electronics for the electromagnetic calorimeter and to purchase 100 silicon photo-detectors and 100 modules from MCS to develop a proof of principle. This R&D can be applied to any calorimeter being designed that uses these silicon photo-detectors. The cost of the electronics engineer time at $100/hour is $20K. The cost of the 100 Silicon Photo Sensors is estimated to be $4K and the cost of the modules we estimate at $10K. The total is $34K. This cost is for the first year only. The cost for the second and third year is associated with the construction of the test calorimeter to go into a test beam.
- To develop the extruded scintillator program requires the construction of appropriate tooling and die and the purchase of 60 bars 150 mm wide by 1000 mm long by 2 mm thick. The estimated cost as provided by Fermilab with labor and indirect charges (16.1% M&S, 30.35% Labor) is $49.83K. This total cost is distributed between 2 years with the tooling, die, some materials and some labor in the first year.
- The cost estimate to carry out the FEA to construct the tungsten panels and simulate a module is as follows: 0.5 month of Prof. Qi's salary which amounts to $4,208, the salary of a student doing a master's thesis on this

work which amounts to $23K, and the cost of the Tungsten material, etc. which costs $6K. The cost of the Tungsten for the test beam module is estimated at $85K

The total cost for 2005 is $154,528 and the added overhead of 48.7% is $37,237.

3 Year Budget Table

Duration: 1-1-2005 to 12-31-2007

Principal Investigator: Uriel Nauenberg

ITEM	2005	2006	2007
A. SALARIES AND WAGES			
(on Campus)			
Faculty:			
Prof. Jerry Qi			
100% time 0.5 mos. summer	4,208		
Staff:			
Graduate Student:			
Jason Gray			
50% 9 mos. AY	16,516	17,135	
100% 2 mos. Summer	7,491	7,772	
Mech. Eng. Student(To be named)			
50% 9 mos. AY	15,006		
100% 2 mos. Summer	6,806		
To be named			
50% 9 mos. AY			17,778
100% 2 mos. Summer			8,063
Total Salaries and Wages	50,026	24,907	25,841
B. FRINGE BENEFITS			
Faculty:21.2%	892		
GRAs:3.2%	1,466	797	827
Total Fringe Benefits	2,358	797	827

ITEM	2005	2006	2007
C. PERMANENT EQUIPMENT			
100 Silicon Photo Sensors	4,000		
4,600 Silicon Photo Sensors		46,000	
100 MCS Electronic Modules	10,000		
2,300 MCS Electronic Modules		69,000	
2,300 MCS Electronic Modules			69,000
Tungsten Plates for Testing	6,000		
Lamination Material+Labor	2,000		
50 50cm x 50 cm Tungsten Plates		85,000	
Extruded Scintillator Tooling	10,000		
Extruded Scint. Die Develop.	2,000		
Extruded Scintillator Panels Prod.	18,915		
Extruded Scintillator Panels Prod.		18,915	
500 Scintillator Fibers		5,000	
2,300 Analog to Digital Con.		23,000	
2,300 Analog to Digital Con.			23,000
Total Permanent Equipment	52,915	246,915	92,000
D. Other Direct Costs			
Electronics Support	20,000	10,000	5,000
Materials and Supplies	1,000	5,000	5,000
Tuition Remission:1 GRA (res)	2,794	3,144	3,537
Tuition Remission:1 GRA (non-res.)	22,434		
Total Other Direct Costs	46,229	18,144	13,537
E. Travel			
Travel to Meetings to Present Results	3,000	3,000	3,000
Travel to Test Beams			6,000
Total Travel	3,000	3,000	9,000
F. TOTAL DIRECT COSTS	154,528	293,762	141,204
G. INDIRECT COSTS(48.7%)	37,237	21,415	22,377
H. TOTAL COST	191,766	315,177	163,581

Bibliography

[1] Tsukamoto et. al. Precision Studies of Supersymmetry at Future Linear e^+e^- Colliders*Phys. Rev. D* **51,** 3153 (1995).

[2] Multi Channel System Corp., distributor Wiener US, 300 East Auburn Ave., Springfield, Ohio, 45505.

[3] Tyvek, DuPont Corp., Richmond, Virginia.

[4] 3M Corporation, Kay Bidwell, KMBidwell@MMM.com