A LIQUID ARGON FORWARD CALORIMETER PROTOTYPE: BEAM TEST RESULTS

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A prototype of a liquid argon forward calorimeter suitable for high luminosity hadron collider detectors has been constructed and tested in electron beams at BNL and CERN. The linearity and resolution of the energy response and the position resolution from a preliminary analysis are presented. The constant term in the energy resolution is smaller than 5% and the position resolution is smaller than 1 *mm*. Some comparison to other technologies is made.

Introduction

At a high luminosity hadron collider much of the physics interest centers on 'high p_T' events where the natural energy scale is a significant fraction of the center-of-mass energy of the proton-proton collision. Therefore most of the final state particles are produced centrally. Coverage out to $|\eta| = 3$ is generally adequate for such events. However many interesting physics processes include weakly interacting particles, such as neutrinos or more exotic particles, which escape detection. In order to better reconstruct the kinematics of such reactions it is necessary to detect all of the final state particles, many of which have $|\eta| > 3$. So for $\not{E}_T$ physics, calorimetric coverage well beyond $|\eta| = 3$ is crucial. Examples are SUSY and a heavy Higgs $\to ZZ \to \ell\bar{\ell}\nu\bar{\nu}$. The natural scale for $\not{E}_T$ physics will be a moving target. When the LHC turns on, the Fermilab Tevatron will likely have covered the range where $\not{E}_T < 100$ GeV. Early in the running at the LHC when only low luminosities are available, $\not{E}_T$ in the region of 100 GeV will be of considerable interest. At higher luminosities $\not{E}_T$ of several hundred GeV will be most interesting.

A quite different physics area of relevance to a forward calorimeter is jet tagging. When a quark radiates a W or Z, the recoil quark will have a p_T of order the W/Z mass and large $|\eta|$. The jets from these recoil quarks can be detected in a forward calorimeter and used to tag WW scattering for instance.

Extensive studies of the physics requiring a forward calorimeter suggest that the $\not{E}_T$ signatures from SUSY and tagging jets provide the most demanding constraints on the measurement capabilities of a forward calorimeter.

For most calorimeters energy resolution is the critical parameter. However for a forward calorimeter position resolution is also important. In fact, above about $|\eta| = 4$ position resolution (angle resolution) is more important than energy resolution. For this reason forward calorimeters with some longitudinal segmentation have a natural advantage. To some degree they can separate electromagnetic energy from hadronic energy. Since electromagnetic showers are transversely well confined it is easy to achieve the required position resolution. But hadronic showers are a different matter. One can improve the position resolution for hadronic showers considerably by longitudinal segmentation since the early development of a hadronic shower is transversely narrower than the shower integrated over depth. It is also important to have a dense calorimeter so that the transverse spreading of the hadronic shower is minimal. It's worthwhile remembering that the size of a jet at the face of the forward calorimeter is significantly smaller than the transverse size of an hadronic shower at the larger values of $|\eta|$ covered by a forward calorimeter.

The forward region, i.e. large $|\eta|$, is the region where the density and energy of particles from the dominant minimum bias events are highest. At a luminosity of $10^{34} cm^{-2} s^{-1}$ at the LHC and for a forward calorimeter covering the range $3 < |\eta| < 5$ about 7 TeV of energy on average will be deposited in each forward calorimeter in each beam crossing. Particle tracking in this region is hopeless. And calorimeters will be subjected to severe radiation exposure from the electromagnetic and hadronic showers. The high particle energies and fluxes demand rad hard materials and fast response to avoid pile-up. Exposures in excess of hundreds of MRad/yr are expected. In this region the environment is most hostile and the farthest removed from our experience at lower energy, lower luminosity hadron colliders.

Because the forward calorimeters at high luminosity hadron colliders are required to satisfy many constraints, designers are forced to make many compromises in the course of optimization. For instance technologies suggested for the forward region do not have as good energy resolution as a barrel calorimeter in order to address the other demanding requirements.

We have developed a liquid argon calorimeter concept which meets all the demands and which, we believe, provides the best performance compared to the other concepts so far developed. 1) The response is fast, of order the bunch crossing time at the LHC. 2) The energy and position resolution are more than adequate to the physics and are significantly better than the competition. And 3) the calorimeter is manifestly radiation hard.

In this report we describe a prototype electromagnetic (EM) module which we constructed. We present preliminary results of its performance from test beam runs at Brookhaven but, primarily, at CERN just a few months ago. Analysis is in progress and much remains to be done. Numbers presented here are likely to change somewhat as we refine our analysis techniques and better understand some of the more subtle features of the prototype.

Not addressed in this report are issues having to do with integrating such a concept into a full LHC detector. This is premature since we do not yet understand such issues in sufficient depth. However this concept was successfully integrated into the GEM detector design [1] and we were particularly pleased with the result.

The Basic Design Concept

A novel calorimeter design concept pioneered by various members of the the former GEM calorimeter group has been developed into an operating detector prototype by the University of Arizona. The hallmark of this sampling cryogenic noble liquid design is that it employs exceptionally thin active gaps (as small as 100 μm) in order to speed charge collection (as fast as 10 ns) and to avoid the effects of positive ion buildup [2]. These properties, combined with the possibility of using only radiation hard materials in the fabrication, make this design ideal for a high rate and high radiation environment.

The active gaps of liquid cryogen (liquid argon or liquid krypton) are tubular in shape (cylindrical shells). This geometry allows the use of simple fabrication techniques which are readily adapted to 'assembly line' methods, while at the same time maintaining precise control of the gap dimension. That is, this design leads to great economies in fabrication, while at the same time preserving tight tolerances. This clean geometry also allows for very fast transfer of collected charge from the electrodes to the electronics. There are no loops and turns in the connections, in contrast to parallel plate geometries, so the inductance in the circuit is quite low leading to fast time constants [3].

In the Arizona design, solid rods of metal absorber (brass, steel, tungsten) are inserted in metal tubes with an inner radius larger than the rod radius by an amount equal to the desired gap. Mechanical spacing and electrical standoff in the gap are achieved by winding an insulating thread (having a diameter equal to the gap) around the rod in a spiral before inserting it into the tube. A typical rod and tube assembly is shown in Figure 1. The particular materials and dimensions shown in this figure are those for a prototype built at Arizona for a testbeam run at Brookhaven, as described more fully below.

The rod and tube assemblies are then inserted into an absorber matrix of the same metal to make up the complete calorimeter assembly, as shown in Figure 2. To make the calorimeter as homogeneous as possible, we have arrayed the many tube axes parallel to each other, with the tube centers forming a 'hexagonal' (equilateral triangular) matrix. The parallel tube axes insure that the sampling fraction is constant throughout the calorimeter volume. Particles are intended to enter the calorimeter through a face with tube ends, so that the 'z axis' of the calorimeter is parallel to the tube axes.

This geometry has several parameters which may be varied to optimize the calorimeter for a given application. Thinning the gap and leaving the other parameters fixed will lead to faster charge collection, reduced susceptibility to positive ion buildup, lower sampling fraction, and higher capacitance per tube. Thin active gaps also minimize the probability that incident or shower particles will travel any appreciable distance down the gap before encountering absorber. This effect makes the sampling more uniform. For a hexagonal matrix, there is also some small variation possible in the ratio of tube radius to the distance between tube centers, but the configuration for the Brookhaven prototype, with this ratio set to 1:3, is roughly optimal for uniform response. If one keeps this ratio fixed, the distance between centers may be tuned to the application, and made small compared to the electromagnetic shower (Moliere) radius, the hadronic shower radius, or a typical jet radius at the given distance of the calorimeter from the interaction point. As the distance between centers is made smaller, the calorimeter will become more homogeneous in its response to the given object to be detected; but the tradeoff, of course, is cost.

An additional effect which can change the optimization is that in some real applications, such as a forward calorimeter, there may be unavoidable material in front of the calorimeter (beampipe, flanges, vacuum pumps) which introduces several radiation lengths of absorber in front of the calorimeter. In such cases a coarser tube structure is optimal because of the spreading of electromagnetic showers (or shower components) in these preradiating materials.

This geometry lends itself naturally to electronically ganging tubes to form axial towers in η and ϕ. It is also very natural in this technology to make a full calorimeter out of several longitudinal segments, allowing the formation of pseudoprojective cells. The spacing between tubes should increase from one depth segment to the next at least in proportion to the distance from the interaction point. Position resolution for hadronic showers and jets may be optimized by making the first longitudinal segment approximately 2λ deep and using this depth for centroid determination. Tail fluctuations are thus left out of the position measurement. This becomes important in forward calorimeters where at larger $|\eta|$ the angular resolution is the dominant contribution to the p_T resolution. Longitudinal segmentation also allows for improvement in jet resolution through weighting procedures. The fraction of jet energy observed in the first longitudinal depth segment reflects the prompt π^0 fraction in the jet, and fluctuations in the calorimeter response due to fluctuations in jet fragmentation are reduced by the weighting procedure.

This geometry also allows for the possibility to make the calorimeter extremely radiation hard. For example, the tube, rod, and absorber matrix are metal (brass in the EM prototype) and the cryogen is liquid argon or liquid krypton. These are not degraded at all by ionizing radiation. The insulating thread should be a quartz fiber with a cladding of Kapton. The mechanical tolerance to ionizing radiation is acceptable by several orders of magnitude. These are the only materials near electromagnetic shower maximum. The readout electronics is all located remotely from the forward calorimeter outside the radiation field and need not be rad hard. The electrical connections between the rods and the cables must be chosen with care to ensure radiation resistance. And these connections can be at the end of the module least subjected to radiation.

Mechanical and Electrical Design

We constructed a prototype of a first longitudinal depth segment for a forward calorimeter with design parameters optimized for a testbeam run on electrons at 8 GeV at Brookhaven National Laboratory. To improve the signal to noise measurement at these very low energies we employed a gap of 250 μm, somewhat larger than is needed in a typical forward calorimeter application, where the gap might approach 100 μm [4]. The liquid argon active tube gaps have an inner diameter of 4.5 mm, with center-to-center distance on the triangular matrix of 7.5 mm. As shown in Figure 3, 374 tubes are in the matrix, with 192 of them instrumented. The active tube gaps are 25.4 cm in length, leading to an active depth of the calorimeter of 14.4 radiation lengths and 1.30 absorption lengths. Absorber matrix, tubes, and rods are all yellow brass. See Table I.

The absorber matrix is constructed of a stack of round plates with a hexagonal array of drilled holes to allow the insertion of the tube assemblies. The absorber plates at each end of the stack have precision reamed holes which both accurately locate the tube assemblies and establish electrical contact with the tubes. The stack of absorber plates is then bolted together and placed inside an outer sleeve which locates the two end plates with respect to each other. Photos of these plates and stack are shown in Figures 4 and 5, and a slice of the prototype calorimeter assembly is shown in side view in Figure 6.

Holes were drilled in one end of the rods and brass wire pins were soldered in place. The rods were wound with four turns of nylon thread (quartz with Kapton was not available on short notice) on a jig, invented for ease of manufacture, and inserted into the tubes. Delrin plugs were then press fit into both ends of the tube to hold the rod in place during assembly. These plugs also act to prevent the thread from unwinding during thermal cycling. Holes in these plugs allow the rod contact pins to emerge and liquid argon to flow into the gap. A printed circuit board is then attached to one end plate of the module, with the tube pins emerging through holes in the board. Traces on the board create an electrical ganging of the tube assemblies into pairs to accommodate the 96 channels of electronics which were available for the readout of the module. (θ-ϕ ganging patterns would be used to create η-ϕ towers in a real calorimeter).

Figure 7 is an isometric view of the prototype in its testbeam configuration. Shown are the calorimeter, the dewar top plate and inner support structures, and the cabling inside the dewar. An excluder volume of rohacell sits in front of the calorimeter. The Faraday cage containing the preamplifiers/shapers for 96 channels of readout (not shown) mounts to the top plate on the large feedthrough on the right. The box beside the calorimeter is the beta ionization cell [5]. A photograph in Figure 8 shows a number of these same features. The module was operated in a cryostat based on a MVE K1 dewar with an O-ring sealed top plate. The cryostat was charged with about 40 liters of liquid argon and cooled by means of a heat exchanger coil with liquid nitrogen refrigerant. Normal operating pressure in the dewar was 3 PSIG. Cooling was controlled by an all-pneumatic circuit avoiding the use of electrically operated solenoid valves and their associated electrical noise. A Moore Products pressure transmitter sensed the cryostat pressure and proportionally controlled the flow of liquid nitrogen through the cooling coil using a valve on the warm side of the coil.

Argon purity is an important issue in liquid noble gas calorimetry due to signal loss through attachment of electrons to electronegative species. Oxygen contamination is often the most serious concern. Argon purity was monitored using a beta ionization cell developed for the D0 experiment at FNAL (labeled 'Blazey Box' in Figure 7). This technique indicated an oxygen contamination of 0.6-0.7 ppm. Argon purity was also checked after the run using a Delta F Oxygen Analyzer which indicated an oxygen contamination of 0.5-0.7 ppm.

One consequence of the very thin active gaps is that the drift field of (nominally) 12 KV/cm in the gap is provided by a 315 volt power supply in this prototype, and would be only 120 volts for 100 μm gaps. In the Brookhaven test, clean electron showers at 8 GeV were observed in the calorimeter with as little as 12 volts supplied to the gaps.

A simple schematic of the electronics used for the prototype is shown in Figure 9. The preamplifier/shaper modules use a common base front-end with a unique feedback arrangement that gives the input a stable and controllable input impedance over a large dynamic range. The impedance is set to 50 ohms in order to match the coax cables that connect to the calorimeter and thereby avoid problems that might result from reflections. The design of the preamplifier allows future versions of the system to easily accommodate other cable impedances that might be required. The shaper is set at 50 *ns* and has a 50 Ω output for driving cables that attach the electronics module to a Track-and-Hold system. The outputs of the Track-and-Hold modules are attached to CAMAC based 11-bit Analog-to-Digital Converters which are read by the on-line computer.

The preamplifier box for the calorimeter is mounted directly on top of the cryostat and consists of a single chassis that contains 6 mother boards, each containing 16 preamplifier/shaper modules, and a control board which connects the mother boards to a remote on-line computer for control of the calibration system. Each of the 6 mother boards has an integral calibration system that is used to monitor the 16 amplifier/shaper modules on that mother board. The levels and trigger for the calibration system are sent over a parallel interface by a remote computer connected to the control board. The present design pulses all 16 channels simultaneously with the same level, although future designs may allow each channel to be pulsed independently or in combination.

The October 1993 Test at CERN

The first test run of this prototype occurred at Brookhaven in July and August of 1993. Data with 2, 4, 6, and 8 GeV electrons and pions were obtained. See Appendix B. Online and preliminary offline analysis of this data set showed that the prototype was performing as expected. When presented with the possibility to test it at higher energies at CERN, we seized the opportunity to demonstrate its performance there. Unfortunately, because of the short time scale, there was no time to manufacture a deeper prototype, and the 14.4 X0 depth chosen for Brookhaven energies leads to the need to make longitudinal leakage corrections at CERN energies to determine the intrinsic resolution and linearity of the detector.

The CERN test took place during October of 1993 in the H8 beamline in the North Area. A secondary electron beam was available at 200 GeV/c and tertiary electron beams, at 150, 100, 50, 20, and 10 GeV/c. In addition to the beam energy, other parameters of the test configuration were varied:

1) The calorimeter module could be rotated through small angles about the vertical axis (with $\theta = 0$ indicating that the tube axes were parallel to the beam). Data were taken at various angle settings between $\theta = 0.5^\circ$ and $\theta = 3.4^\circ$.

2) The amount of material in front of the calorimeter could be varied. The

minimum in front of the module was the two stainless steel walls of the dewar, the excluder block, the brass front plate of the calorimeter module, and the plastic end plug: a total of about 0.8 X0. In addition, aluminum blocks could be placed on the platform in front of the cryostat to add 1.1, 2.2, or 3.3 X0 to this minimum. Data were taken with varying amounts of this upstream material in order to simulate the effects of structures which would be present in a full collider detector.

3) Data sets were taken at various active gap voltages to map out the high voltage curve of the apparatus.

A simple diagram of the active elements of the experimental configuration appears in Figure 10. This is actually a side and top view event-display taken from the online VAX, but it shows somewhat schematically the major components of the apparatus. The first thing encountered by the beam, approximately one meter upstream of the calorimeter module, was scintillation counter S2 (2 by 4 vertical by 0.3 *cm*), which together with S1 (2 by 2 by 0.3 *cm*) formed the primary coincidence trigger, with the transverse beam envelope being determined by the dimensions of S1. Surrounding the S1 and S2 region transversely was a plane of veto counters insuring that the trigger did not include particles which had interacted in upstream material and produced halo particles.

The next element downstream was an XY hodoscope consisting of 1 *mm* scintillating fibers in the fine central areas, with 28 elements measuring the horizontal direction and 12 measuring the vertical for a total distance of 6 *cm* horizontally and 2 *cm* vertically. The next downstream element, and the last before the cryostat, was a 'dE/dx' counter, a scintillator 1.3 *cm* thick for further identification of electrons which have not interacted before entering the cryostat. Following the cryostat was a lead glass block about 10 X0 deep followed by a bank of leakage counters, L1,2,3. The leakage counters were to detect hadronic showers resulting from pion contamination in the beam. The lead glass measured the leakage energy associated with electron showers in the calorimeter. After an 80 *cm* thick concrete block and about 4 meters downstream was a scintillation counter to detect muon contamination in the beam.

The trigger circuit for this test run was very basic, and is pictured in Figure 11. Its essential features are as follows: The primary trigger is the coincidence S1·S2, with S2 defining the timing edge for the Track-and-Hold and ADC gates. Upstream interactions are vetoed via the VETO wall, which has a path through the VETO-OR to the main trigger unit, TRIG. Other veto sources include (1) being between spills (the SoS and EoS circuit), (2) having the data acquisition busy (DAQ VETO), and (3) an early-pileup veto to prevent there being two particles in the calorimeter at the same time (PILEUP). The

TRIG signal performed a number of tasks: (1) put the Track-and-Hold into hold mode, (2) gate the ADC's and latches, and (3) send an event interrupt to the data acquisition on-line computer.

The data acquisition system was set up and the software written at the University of Arizona. The Track-and-Hold units were borrowed from Brookhaven for this test. The 96 voltage levels at the outputs of this system (one for each calorimeter electronic channel) were sent to a Lecroy FERA 11-bit ADC system for digitization, and read from there via the FERA/CAMAC interface. Other ADC's, latches, scalers, etc., resided in the standard CAMAC crate, which was connected via a DSP CAMAC interface to the data acquisition computer. This computer was an industrial rackmount IBM-PC clone whose only other interface was to a dedicated ethernet. The primary task of the online computer was to read data and ship it to a remote disk via ethernet. It also managed calibration and pedestal runs, and was capable of making histograms and plots. For example, it controlled the sequence of calibration voltages through a DAC board directly on the PC bus. The online system had a convenient multi-window framework written in TURBO-PASCAL. This system was capable of acquiring up to 2400 events per spill, and did not limit the data rate during the CERN test, since the maximum trigger rate was approximately 1200 per spill.

The data were logged to remote disk via the ethernet interface. In the CERN test, the 'remote' machine was a VAXStation 4000 Model 60 sitting next to the rack containing the online computer. This 'offline' machine processed calibration runs, calculated gain constants, and performed analysis on data runs, either as they were being taken, and/or during experimental down times. The diagnostic power in both computers was needed to assure the quality of the data and to develop the run plan dynamically as the test proceeded. One of the many tools used while running was the one-event lego style display of calorimeter pulse-heights. An example of such a display is shown in Figure 12 for a 200 GeV incident electron.

Calorimeter Resolution and Linearity

The energy resolution of the calorimeter prototype had a number of contributions. Here we catalogue the major sources, noting both the magnitude of the effect for the calorimeter prototype module as it existed in the CERN testbeam run, as well as the anticipated contribution in a realistic forward calorimeter. (Many of the design, electronic, and response parameters of the testbeam prototype, as calculated ahead of the test beam runs, are summarized in Table I.)

Electronic Noise. The noise associated with the detector capacitance and cabling reacting with the intrinsic amplifier noise is the only important source of irreducible electronic noise. Each active tube in the calorimeter is 25.4 *cm* in length, with an inner diameter of 4.5 mm and an outer diameter of 5.0 mm (250 μm gap). Filling with liquid argon gives a capacitance of 200 pF, and a characteristic impedance of 5 Ω. Ganging the tubes by two, the detector capacitance per electronic channel is thus 400 pF. The cable connecting each ganged tube pair to its preamp is 5 ns in length, with a characteristic impedance of 50 Ω.

The amplifier characteristics, and the parameters above, are very close to those used in an extensive analysis and benchtop study done by Chase *et al.* [6]. That study gives an equivalent noise charge (ENC) in units of electrons RMS of approximately 7000 to 14000 per channel for our configuration: we assume 14000 to be conservative. The dE/dx weighted sampling fraction of the prototype module is 1.54%, the fraction lost due to the shaping time (ballistic deficit) is 5.5%, and detailed simulation shows that the e/MIP ratio is 0.90. All of these factors combine to give a charge calibration of 260000 electrons per GeV.

When one combines ENC = 14000 per channel with this charge calibration, the resulting noise is 0.050 GeV per channel. For the effect on electromagnetic shower resolution, if one clusters within 2.0 Moliere radii, this amounts to summing the noise (in quadrature) in 21 channels in the current prototype, yielding a noise of 0.23 GeV per shower. In the CERN test where only 11-bit ADC's were available we were forced to lower the gain on the preamp and shaper circuits (about 30,000 electrons per ADC count) so that a 300 GeV EM shower, concentrated in a single channel, would not overflow the ADC's. This reduced the preamp noise well below one ADC count RMS. But the ADC's themselves and the Track-and-Holds introduced some noise of order 2 ADC counts RMS. On top of this there was a small amount of coherent noise which was an artifact of the provisional electronics used and which will require application of a coherent noise matrix for correction. Nevertheless this noise was significant only at the lower energies. And in the Brookhaven tests where our gains were higher we were able to approach the fundamental noise limits. See Appendix B.

In a realistic forward calorimeter design, the energies of interest will be even higher than the CERN test. This leaves some room in the optimization to increase the capacitance per channel considerably. This allows for ganging into η-ϕ towers and (if needed) for making the gaps thinner.

Crosstalk. A compromise had to be made for the BNL and CERN tests in using twisted pair cable between the preamps and the Track-and-Hold units instead of coaxial cable. (These lines were also driven single-ended instead of differentially in the test.) As a result, this far from optimal configuration had a crosstalk coupling of 2% to 4% to adjacent channels. To correct carefully for this, the 96 channels were pulsed one at a time and the crosstalk matrix was determined (to non-adjacent channels as well). This matrix is applied to each event as the first step in the data processing. For the test run, these corrections lead to significant resolution effects. But in a final detector configuration it is anticipated that the crosstalk would be negligible (though such a correction matrix might still be applied).

Sampling Fraction. As noted above, the calorimeter prototype module made for the current tests has a dE/dx weighted sampling fraction of 1.54%. The sampling fluctuation associated with this sampling fraction induces a stochastic term which dominates at intermediate energies and is sizeable for the full range of energies studied at CERN. Unfortunately it is not possible to give a back-of-the-envelope estimate of this term since the sampling fluctuations are not simply functions of the sampling fraction. In reality they also depend on sampling frequency and details of the detector geometry (plates vs. tubes for example). The only reliable way to get estimates of the stochastic term is via the detailed GEANT or EGS4 simulations with low cuts. To date, we have had manpower and CPU time for only one comparison of a detailed simulation run with a Brookhaven data point at 8 GeV, which had a resolution just under 13%. The simulation agreed with the observed distribution, and would imply a stochastic term of $34\%/\sqrt{E}$. See Appendix B. But this result is very preliminary, and simulations of the CERN data points have yet to be completed.

For realistic forward calorimeters we anticipate that this technology might be used with gaps as small as 100 μm and sampling fractions as low as 0.5%. This might increase the stochastic term. But in the energy regime of a forward calorimeter, this is acceptable. The particle and jet energy resolutions will be dominated by the constant term which will be dominated by dead material in front of the calorimeter, and the p_T resolution will be dominated by the position resolution in the calorimeter (which, in an otherwise perfect calorimeter, is limited by pileup from the underlying event).

Dead Material and Leakage. In any realistic forward calorimeter, there will be several radiation lengths of material between the interaction point and the front of the calorimeter. In the testbeam run, data points were taken with varying amounts of material in front of the calorimeter to map out the effect on the resolution. In addition, the testbeam calorimeter was shallow compared to an optimal forward calorimeter first longitudinal depth segment, so some leakage occurred out the back of the calorimeter module. After passing through approximately 1.0 X0 of liquid argon and cryostat walls, this energy was measured by a lead glass block so that corrections might be made. These dead material effects lead to a constant term contribution to the resolution. Notice however that neither of these sources of constant term is intrinsic to the calorimeter design. A real forward calorimeter would be sufficiently deep to avoid longitudinal leakage, and most of the material in front of the calorimeter will come from beam-related structures, and be largely independent of forward calorimeter technology choice.

Because the calorimeter module used in this test was shallower than optimal for these energies (14.4 X0 instead of 25 to 30 X0), a leakage correction was applied to the data using the observed energy in the lead glass block downstream of the calorimeter. This block was not ideally placed, since there was approximately 1.0 X0 of material between the back of the calorimeter and the front of the block. Normally one would just calibrate the block and add the leakage energy. But with this dead material in between, much of the leakage energy is not seen, and the starting depth of the shower which is sampled depends (on average) on the amount of dead material in front of the calorimeter. For this reason, the gain constant was determined by minimizing the energy resolution for the total $E_{calorimeter} + G \times E_{leadglass}$, with a different G for each dead material depth used. $G(X0)$ turned out to be a weak function of X0 and was not a function of incident energy for a given X0.

Clustering. The purpose of clustering is to reduce the electronic noise contribution from 'unhit' cells. The algorithm used in the current analysis is primitive and conservative. First, the shower centroids in x and y were found from the sum over all cells in the calorimeter. This centroid position was used as the seed for the first iteration of the cluster finder. In each iteration, the energy in a 5.0 cm by 5.0 cm square centered on the current centroid was summed for the energy total. These clustering dimensions were used at all shower energies, even though they are larger than necessary for containment at the lower energy points. Cells which were partially overlapped by the boundary square had a fraction of their energy included equal to the fraction of the cell area overlapped by the square. Centroid x and y sums accumulated the positions of each cell weighted by the energy (or fractional energy) in that cell. On each iteration a new centroid position was found and used to seed the next iteration. After two iterations in which the centroid positions were identical, the cluster was declared 'found,' yielding the final energy and position for this shower.

Position Dependence. Because electromagnetic shower cores are very tightly collimated and the core widths are comparable to the tube diameters used in the calorimeter prototype, there is some correlation between the observed energy and X and Y positions of showers. When there is no material in front of the calorimeter and the entrance angle is near zero degrees, this modulation is as much as 8% peak to peak, but with 3.3 X0 in front and at small angles typical of those in a real forward calorimeter it damps to approximately 2.5%. Since the shower centroid is located solely on the basis of calorimeter information, this may be corrected for. This position-dependent correction has been applied in analyzing the current data sets.

To preserve normalization, the observed response was mapped into a unit cell of the calorimeter, the mean was determined, and the correction was applied as a percentage above or below this mean. Note that even without any correction, this inhomogeneity would be below the constant term due to dead material for realistic forward calorimeter configurations.

Trigger Criteria. To select good electrons, it was required in software that the VETO, LEAK, and MUON counters fall below a threshold value. The VETO requirement removed upstream interactions and beam halo. The MUON requirement reduced the similar contamination due to beam muons and further cleaned up pions which punched through the concrete block into the muon counter.

In addition, to reduce pion contamination in the beam, an energy and material (in front) dependent cut was made on the LEAK counters. This would record large pulses when a beam pion interacted in the calorimeter or lead glass and the resulting hadronic shower emerged into this counter.

Data Analysis and Corrections

In the short time since the end of the CERN test in October, we have had time to study three samples of data, with 0.0 X0, 1.1 X0, and 2.2 X0 of aluminum in front of the cryostat, all at 3.4°. When the irreducible material is included, these correspond to front material depths of 0.8 X0, 1.9 X0 and 3.0 X0. This represents roughly 30% of the full data set taken during the CERN testbeam run.

All events failing the trigger or LEAK counter criteria were ignored. The analysis sequence for the calorimeter data from each event was fairly straightforward, and involved the following basic steps:

(1) Subtract the pedestal average for each channel from the raw pulse height in that channel.

(2) Apply the crosstalk correction matrix.

(3) Multiply by the gain constant determined for each channel through calibration runs, putting the data now in units of electrons.

(4) Find the x and y centroids of the shower using all cells in the calorimeter.

(5) Apply various clustering algorithms to sum only cells in the vicinity of the shower center and thus reduce the noise due to unhit cells (see previous discussion on clustering). New values of x, y, and the shower energy result from this clustering.

(6) Correct the energy for position dependence. This correction is largest

when there is no material in front, and becomes negligible compared to other resolution sources as 'realistic' material depths are added (see previous discussion on position dependence).

(7) Add in the leakage energy from the lead glass (see previous discussion),

This sequence was followed for all data sets presented in this preliminary analysis. We now give the results.

Observed Noise. Figure 13 shows the energy response and electronic noise contribution in these data with good electrons at 20 GeV/c and 150 GeV/c. Note that there are almost no 'tails' in the data so a Gaussian is an excellent representation of the energy response over at least three orders of magnitude. It is clear that the electronic noise is a large fraction of the resolution at 20 GeV/c and negligible compared to other sources at higher energies, as one expects from a '1/E' term.

Observed Linearity. Figure 14 shows the mean observed energy vs. the beam energy for energies in the range from 10 to 200 GeV/c when there is no added material in front of the detector (0.8 X0 total). The linearity is quite good. The difference plot in the same figure shows the deviations at most points to be within 1.5%. 10 GeV is anomalous, with an excursion of -5.2%. Figure 15 shows the linearity and difference plot with 1.9 X0 of total material in front. Here all data are within 0.6% (no 10 GeV data were taken here). Figure 16 shows the same plots for 3.0 X0 total material in front. Once again, the linearity is quite acceptable, with most points within 0.8% and 20 GeV at 4.5%.

Energy Resolution Parameters. The energy resolution has been determined from fits within 3.0 σ of the peak for all material depths and energies listed above. Figure 17 shows the resolution as a function of energy with 0.8 X0 total material in front, along with the curve resulting from the fit for stochastic, constant, and noise terms. Figure 18 has the same plot with 1.9 X0 of front material, and Figure 19, for 3.0 X0. The table below gathers the parameters of these fits in one place for comparison:

Energy Resolution Terms

Total Material (X0)	Stochastic Term (%)	Noise Term (GeV)	Constant Term (%)
0.8	49.2	1.9	3.7
1.9	40.9	2.4	4.2
3.0	32.8	3.1	4.4

With only five data points, and fitting for three unknown parameters, there is some instability in these fits because of the correlations among the parameters. Nevertheless, we appear to be measuring stochastic terms with realistic material in front of the calorimeter in the range of $35\%/\sqrt{E}$, noise terms around 2.0 to 3.0 GeV, and constant terms of about 4%. This stochastic term agrees with what was observed at Brookhaven, and the constant term is not unreasonable when compared with our expectations of what might be induced by dead material fluctuations (see Appendix A.) We await the detailed GEANT simulations before making further comparisons.

Resolution as a Function of Dead Material. Figure 20 shows the energy resolution at 150 and 200 GeV as a function of the dead material in front of the cryostat. A curve through the data would have reasonable magnitude but no obvious trends. We expect the curve would start to slowly rise as additional dead material is added.

Position Resolution. The fine granularity of this prototype allows for very good position resolution. Table II shows the position resolution under various conditions. The second and third lines differ in that the lead glass counter was used to correct for longitudinal fluctuations in the third line. The * indicates that a special correction procedure was used here. In the second line longitudinal fluctuations at 3.4° feed into the x position resolution. In the fourth line the incident angle is so close to normal incidence that longitudinal fluctuations couple too weakly to have an affect.

Conclusions

Preliminary analysis of data from Brookhaven and CERN beam tests of the prototype thin-gap tube liquid argon calorimeter developed at the University of Arizona shows that it is performing as expected, based on analytical predictions and simple simulations. Final results from these tests await analysis of the full data set and the completion of detailed GEANT simulation runs for each data point.

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Appendix A. - Initial Studies of Dead Material and Leakage

In order to estimate the contribution of dead material in front of the calorimeter and leakage out the back to the degradation of the calorimeter energy resolution, special GEANT simulations were undertaken to study these effects alone. A mixture is formed of brass and liquid argon in the correct ratio to model the calorimeter prototype module. The resulting density is 7.95 g/cm^3 and the radiation length of this mixture is 1.61 cm. A GEANT model is then made with a stack (in z) of 31 slabs which are very large in transverse dimension (x and y) and exactly 1 X0 each in depth (z direction). By suitable summing, it is possible in one simulation run to investigate several calorimeter depths with a selection of dead material depths in front.

Since the current prototype module was 14.4 X0, slab sums were formed for both 14.0 X0 and 15.0 X0 deep calorimeters. In addition, for comparison with the results for a deeper calorimeter, 25.0 X0 sums were formed with the same selection of dead materials in front. In this study 150 GeV electrons were generated travelling along the z axis and entering the GEANT model at one face. For each event, as showers developed, the energy sum in each slab was formed. At the end of each event, sums of 14, 15, and 25 slabs were formed with 0, 1, 2, 3, 4, 5, and 6 X0 of dead material in front.

Figure 21 shows the resolution (percentage RMS) due to dead material and leakage fluctuations for each of the conditions simulated. The general trends are interesting. With no material in front, the resolution is due only to leakage fluctuations out the back. With a lot of material in front, the resolutions converge to an approximately universal curve, where the fluctuations in the front dead material are dominant. In the intermediate regime, shallow calorimeters show a pronounced minimum where as the shower origin fluctuates in z, the longitudinal shower profile causes a 'compensation.' That is, if the shower develops early, a lot of energy is lost in the front and little behind the calorimeter. The opposite holds true for late developing showers.

The resolutions in Figure 21 are comparable to the observed constant terms for the three data sets considered in this preliminary analysis. This initial study was intended merely to establish magnitudes and the functional dependence of the resolution on various parameters. The final analysis will require detailed GEANT simulations for each depth, energy, and angle setting of the calorimeter.

Appendix B. - Detailed GEANT Simulations

One of the primary goals of the Brookhaven and CERN testbeam runs has been to make sure that when all effects are accounted for, a detailed simulation properly reproduces all measured quantities (energy and position distributions) under all running conditions. There are various parameters such as energy cuts and step sizes to tune in all electromagnetic (and hadronic) shower simulations. The hope is that a physically sensible choice of these parameters will lead to a 'tuned' simulation which can be trusted to predict how the thin tube calorimeter design will perform when its dimensions or absorber materials are changed (within reason).

Beginning in 1992, Peter Loch wrote a detailed GEANT description of the calorimeter including tube assemblies, the front plate and other front components, and the rear plate and components. This simulation includes a realistic description of the irreducible and additional materials in front of the calorimeter module, and is being enhanced to include the downstream structures, lead glass block, etc. Low electromagnetic cuts and small step sizes (automatically selected) must be used because the tube structures are spatially small and the sampling fraction is small. This makes the simulation run very slowly. At the same time, the studies often focus on the behavior of small tails of distributions, so that the simulations must be run for high statistics.

To date there has been CPU time and manpower sufficient only to look at a subset of the Brookhaven data, but what we see there is very encouraging. Figure 22 shows a comparison of the detailed simulation with data at 2.0, 6.0, and 8.0 GeV. The solid points with error brackets are data, while the histogram style line is the simulation. The correspondence between simulation and data is quite good, and the results are even more dramatic when one notes that this calculation is *absolute*. That is the simulation signals were scaled in terms of charge in units of electrons equivalent. The same was done with the data, and in this case there are corrections, for example the ballistic deficit correction and the attachment due to impurities. The slight shift between data and simulation at 2 GeV results from a still-imperfect model of the upstream material in the simulation.

The final analysis of the Brookhaven and CERN full data sets will include detailed simulation for each running condition. By this route, we will know we can trust both the detector, and the ability of the detailed simulation to predict its behavior under different conditions.

Appendix C. - Technology Comparisons

As best we know few technologies are as far along in testing performance characteristics as is this Liquid Argon Tube Electrode Forward Calorimeter design. In this Appendix we assemble all known test beam results. Since some technologies have data at only one beam energy we have constructed a table appropriate to the least common denominator. In cases where more data is available we have chosen results at energies or angles which showcase the technology. The column labelled 'ADC Gate (ns)' is meant to denote the timing used in the test. In the case of the liquid argon prototypes it is actually the peaking time which is quoted. The wide gates used by some technologies is not meant to imply that shorter gates could not have been employed, only that timing was not a priority for the quoted test.

Test Beam Results

Technology	Volume Sampling Fraction	Angle to Beam	Energy Resolution	Electron Energy (GeV)	ADC Gate (ns)	Ref.
Liq Argon Tubes	7.7%	3.4°	5.2%	150	50	
Liq Argon Tubes	34%	3.0°	21.6%	3	20	7
Liquid Scintillator	11%	90°	15.4%	10	100	8
Liquid Scintillator	11%	9°	18.7%	15	100	8
Quartz Fibers	7%	9°	25.1%	10	100	8
High Pressure Gas	25%	9°	8.0%	100	80	9

The first table entry is for our prototype at one energy. Following this are results from another liquid argon tube prototype. The resolution is entirely consistent with the stochastic term we measure. Also, in the table, two different spaghetti style liquid scintillator forward calorimeter prototypes were tested. The first had rigid capillaries while the second had flexible capillary tubes. The High Pressure Gas prototype was a tube/rod arrangement large enough to contain hadronic showers and had 4.5 X0 of material in front. Data from 10 to 100 GeV and angles from 1° to 9° were obtained for both electrons and pions so there will be much more information available than implied in this short table entry. For instance a preliminary estimate gives a constant term of 7% and a stochastic term of 4% at 100 GeV and 9°.

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TABLE I
Parameters for
Liquid Argon Tube EM Forward Calorimeter Prototype

Length of brass rod (active length)	254 mm
Active length in radiation lengths	14.4 X0
Active length in interaction lengths	1.4 λ
O.D. of brass rod	4.50 mm
I.D. of brass tube	5.00 mm
O.D. of brass tube	6.35 mm
I.D. of hole in brass absorber	6.73 mm
Sensitive gap	252 μm
Electron drift time	50 nsec
Tube Capacitance	200 pF
Tube Inductance	5.39 nH
Tube Impedance	5.2 Ω
Tube signal velocity	0.82 c
Center-to-center hole separation	7.50 mm
Area of unit cell	48.71 mm^2
of rod	15.90 mm^2
of active gap	3.76 mm^2
of tube	12.00 mm^2
of passive gap	3.91 mm^2
of absorber	13.13 mm^2
Volume sampling fraction	7.72 %
dE/dx weighted sampling fraction	1.54 %
Shaping time	50 nsec
Ballistic deficit (fraction lost)	5.5 %
e^-/MIP ratio	90.0 %
Readout electrons per GeV	261634 electrons
Capacitance of 2 tubes (1 channel)	399 pF
ENC from 1 channel	13392 electrons
ENC from 21 channels (45mm×45.5mm)	61371 electrons
Readout electrons from 9 GeV muon	103353 electrons
Moliere Radius (90% containment)	13.9 mm
High Voltage across gap	315 Volts
Protection resistor for 1 channel	1.0 MΩ
HV current draw/channel when shorted	0.31 mA
HV current draw/channel at 10^5 Hz at 200 GeV for beam spot size of 1cm×2cm	1.8 μA
Voltage sag due to current draw	1.8 Volts

TABLE II
Position Resolution

Energy	Angle	Additional Dead Material	Position Resolution (mm)	
(GeV)	(degrees)	(mm) Al	X	Y
200	3.4	0.0	0.90	0.65
150	3.4	0.0	0.91	0.79
150	3.4	0.0	*0.81	0.69
150	0.0	0.0	0.62	0.72

Figure Captions

Fig. 1. Tube electrode. This is an exploded view of the basic electrode structure of the forward calorimeter prototype. The inner rod is made of absorber material and is held at high voltage, of order 300 volts. The outer tube is held at ground. A spiraled, insulating fiber maintains the gap between rod and tube. Liquid argon fills the gap and the resulting electric field is about 12 kV/cm. Ionization from a shower collects on the rod and, after ganging with other electrodes, is removed by a coaxial cable at one end, not shown.

Fig. 2. The tube electrodes are inserted into a matrix of absorber material. This is a view of a transverse slice of the forward calorimeter prototype. Showers travel at a small angle to the normal to the page. A quarter of a circle of one Moliere Radius is shown in order to set the scale of the size of electromagnetic showers.

Fig. 3. A schematic view of the forward calorimeter prototype from the downstream end. Not all holes in the matrix are filled with electrodes. Electrodes are ganged electrically in pairs so that one electronics channel consists of two tube electrodes. The ganging is indicated by vertical lines connecting two electrodes, one above the other. This figure also indicates our numbering system for the various channels.

Fig. 4. A photograph of three absorber matrix disks.

Fig. 5. In this photograph all but the last absorber matrix disk are stacked on precision locating pins to form the complete module.

Fig. 6. Selected parts of a longitudinal slice through the prototype module showing details of the upstream (right) and downstream (left) faces. The pins which carry the signal charge from the inner rods to the coaxial cables (not shown) can be seen to the far left.

Fig. 7. A CAD/CAM isometric view of the prototype module mounted on its support table. The table is suspended from the cryostat top plate by stainless steel threaded rod with heat interceptors (not shown in this drawing). The copper Faraday box containing the purity monitoring beta cell is on the near side of the module and the Rohacell excluder is shown on the upstream face of the module at the left. The cooling coils are visible just below the top plate. The top of the cryostat can is shown at the bottom of the figure. The whole assembly suspended from the top plate will be lowered into the cryostat can. The flange on the top of the cryostat can is then bolted to the top plate.

Fig. 8. A photograph of the completed prototype module on its stand ready

for insertion into the cryostat. The table to which the module is affixed is suspended from the top plate of the cryostat. The upstream face of the prototype module is shown with 192 tube electrodes inserted (plus some spares). The 92 coaxial cables (plus some spares) which carry signals from each channel to the preamplifiers can be seen at the downstream end of the module headed for the feedthru mounted on the top plate. On the far side of the module in a copper Faraday box is the purity monitoring beta cell. Its two HV and signal coaxial cables can be seen routed to the top plate with spacers to keep them properly separated. Some of the plumbing and feed-thrus can be seen on the top plate. The cooling coils and some heat interceptors can just be made out above the module and below the top plate. The Rohacell excluder which will cover the upstream face of the module is not shown here.

Fig. 9. Analog readout electronics for each of the 96 channels of the prototype calorimeter. The grounding scheme is also shown. Small circles indicate where individual channels are ganged in common with all the other channels, for instance at the H.V. and low voltage power supplies. Note that the signal side of the coaxial cable is at high voltage, i.e. the blocking capacitor is located just before the input to the front-end electronics. This allows *all* electronic components, including the protection resistors, to be remotely located.

Fig. 10. Schematic view of the CERN test beam setup. Trigger counters S2 and S1 are followed by a VETO wall and an XY scintillating fiber hodoscope. A 'dE/dx' scintillator is just upstream of the prototype module. Energy in the module channels is indicated by a LEGO plot viewed on side. The event indicated here is a nice electron trigger. Such displays were available 'online' during the run to aide in monitoring the experiment. A lead glass Cerenkov counter follows the prototype and a wall of leakage counters follows it. The 'mu' counter is hidden behind 80 cm of concrete which is not shown. Numbers on the dE/dx counter, lead glass counter, leakage counters, and 'mu' counter indicate ADC pulse heights.

Fig. 11. Trigger electronics for the CERN test beam run. Not only is the primary trigger indicated but also all the spill control and computer triggers for pedestals and calibration events.

Fig. 12. A LEGO plot of the ADC pulse-heights of the electronics channels of the prototype module. Each 'tower' represents one electronics channel. In this event about half the total energy falls in one tower but there is still appreciable energy in adjacent and next-to-adjacent towers. The whole down-stream face of the prototype is shown in faint outline for orientation. Instrumented and operating channels are covered with towers. For this run four channels were broken. For the next and subsequent runs two of these

were repaired.

Fig. 13. Energy response of the prototype to electron triggers. The data are summed over a cluster of channels within a square area with center at the center-of-mass and size of 5 *cm*. Also shown are the pedestals summed over the same channels.

Fig. 14. Linearity of energy response to electrons from 10 GeV to 200 GeV, with no additional material in front of cryostat (0.8 X0 total). Also shown: deviation from linearity.

Fig. 15. Linearity and deviation plots for 1.9 X0 total material in front.

Fig. 16. Linearity and deviation plots for 3.0 X0 total material in front.

Fig. 17. Energy resolution of prototype forward calorimeter for electrons as a function of electron energy, with 0.8 X0 total material in front. Circles are data. The line corresponds to the fit parameters shown on the plot.

Fig. 18. Energy resolution plot for 1.9 X0 total material in front.

Fig. 19. Energy resolution plot for 3.0 X0 total material in front.

Fig. 20. Energy resolution of the prototype forward calorimeter for electrons at 150 and 200 GeV as a function of the amount of dead Aluminum material in front. In addition to the Aluminum there is another almost 0.8 X0 of irreducible dead material in front.

Fig. 21. RMS fluctuations in the percent of the shower energy contained in the module as a function of the amount of dead material in front of the module for different assumptions of the depth of the module.

Fig. 22. Energy response of the prototype to electron triggers for three energies at Brookhaven. The data points are for real data and the histograms are Monte Carlo predictions. The agreement is good. At Brookhaven the electronic gains were larger than at CERN so the electronics noise was closer to the theoretical values.