9/23/80

BNL 28380

OG 565

MASTER

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Talk presented at the
Summer Institute on Particle Physics at
Stanford Linear Accelerator Center
Stanford, California
July 28 to August 8, 1980

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SAMPLING CALORIMETERS IN HIGH ENERGY PHYSICS

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INTRODUCTION

At our current understanding of elementary particle physics, the fundamental constituents are the photon, quarks, gluons and leptons with a few highly forecasted heavy bosons. Calorimeters are essential for detecting all of these particles. Quarks and gluons fragment into many particles - at high energies so many particles that one may not want to measure each one separately. This group of both charged and neutral particles can only be measured by calorimeters. The energy of an electron needs to be measured by a calorimeter and muon-identification is enhanced by the recognition of a minimum ionizing particle passing through the calorimeter.

There have been many excellent reviews of calorimeters - in particular one written last year by S. Iwata,⁽¹⁾ so we will not attempt a complete exposition here. We will limit our attention to sampling calorimeters - those instruments in which part of the shower is sampled in an active medium sandwiched between absorbing layers. What follows is a very cursory overview of some fundamental aspects of sampling calorimeters. First the properties of shower development will be described for both the electromagnetic and hadronic cases. Then examples of various readout schemes will be discussed. Finally, some currently promising new ideas in calorimetry will be described.

PROPERTIES OF SHOWER DEVELOPMENT

1. Electromagnetic Showers. Sampling fluctuations are usually the largest contribution to the total energy resolution in an electromagnetic calorimeter since usually a large fraction of the energy is deposited in the inert medium. The energy resolution may be expanded⁽²⁾ as a power series in energy (E) as follows:

$$(\sigma/E)^2 = \sigma_o^2/E^2 + \sigma_s^2/E + \sigma_{sys}^2 + \text{higher order terms.} \quad (1)$$

Each of the terms is generally identified with one dominant effect:

σ_o is just the pedestal width which is negligible for high energy showers but limits the minimum signal that may be measured;

σ_s is commonly called the sampling fluctuation term but may include other effects such as photon statistics and excess noise in amplifier gain;

σ_{sys} includes such things as calibration errors amongst the various elements; effects such as shower leakage and saturation contribute to the high order terms.

For calorimeters which use scintillators for sampling, we consider σ_s to be written as follows:

$$\sigma_s^2 = \alpha \, dE/dx \, \Delta x + \beta / (dN/dE) \quad (2)$$

where $dE/dx \, \Delta x$ is the energy loss for a minimum ionizing particle through a single sampling layer in the calorimeter in GeV. α is a semi-empirical constant which depends on the type of shower. For electromagnetic showers it is ~ 2.5 while for hadron showers the data suggests it is ~ 10 .

While this sampling term determines the resolution for the electromagnetic case, once the sampling goes below 0.02 GeV/sample nuclear effects dominate the hadronic resolution. dN/dE is the photon light yield in photoelectrons (p.e.) per GeV. β is a constant that differs from 1 to account for the excess noise in the photoelectron amplification process. Excess noise refers to the fact that the pulse height response due to single photoelectrons has a finite width. For example standard photomultipliers with first dynode gains ~ 5 have β 's ~ 2 .

The p.e. yield can be written as

$$dN/dE = N_0/A(dE/dx)\Delta x \quad (3)$$

where N_0 is the light yield per layer in p.e. per minimum ionizing, and A is an empirical constant equal to ratio between total signal seen from a muon traversing the calorimeter to that amount expected according to dE/dx loss calculations. The signal energy scale is determined from electron showers in that same calorimeter. This number depends on both the showering and sampling media. For example this number is ~ 1.3 for uranium and scintillator.

Combining (2) and (3) we obtain

$$\sigma_s^2 = (\alpha + \beta A/N_0)(dE/dx)\Delta x. \quad (4)$$

Thus for N_0 of $\gtrsim 1$ p.e. per layer per minimum ionizing, photon statistics have a small effect on the energy resolution for the electromagnetic case and $N_0 \gtrsim 0.25$ p.e. for the hadron case.

For electromagnetic showers the $(dE/dx)\Delta x$ term in equation (4) is also proportional to $\sqrt{t}$ where t is the number of radiation lengths per sample. This is demonstrated in Fig. 1 in data compiled by Stone et al. (3)

The lower horizontal group of data is for plastic scintillator and liquid argon sampling. A practical device using plastic scintillator and one radiation length sampling has $\sigma \sim 20\%/E(\text{GeV})$. Proportional wire devices have typically 50% worse resolution for the same sampling rate. This may be due to the Landau fluctuations of the individual electrons in the shower plus the fact that a wide angle electron can travel a longer distance in gas and, therefore, at times produce a larger signal than if the same electron had gone directly into the inert medium. We will have more to say about attempts to improve these two limitations in proportional wire devices later.

Next the longitudinal and transverse development is discussed. L. Cormell⁽⁴⁾ has characterized the average electromagnetic shower shown in Fig. 2. $v = n/n_{\text{max}}$ is the normalized signal plotted against $\tau = t/t_{\text{max}}$, the normalized depth where n is the number of electrons, $n_{\text{max}} = 10 E(\text{GeV})^{0.9}$, t is the distance into the shower in radiation lengths and $t_{\text{max}} = 1.08 \ln (E(\text{GeV})/0.05)$. For example for a 10 GeV shower, the peak occurs at 5.7 radiation lengths and 99% of the shower is sampled by 17 radiation lengths. Lower energy showers are contained in a shorter depth. This can be seen in Fig. 3 where the energy resolution as a function of depth sampled is shown.⁽⁵⁾ For 0.25 GeV showers, the resolution does not improve (in fact it deteriorates) beyond 12 radiation lengths whereas for 4 GeV showers the resolution still improves out to 16 radiation lengths. Therefore in designing an electromagnetic calorimeter, one of the considerations in optimizing the energy resolution is to have sufficient depth.

By contrast the position resolution is rather independent of energy⁽⁵⁾ as seen in Fig. 4. Typically with ~ 1 cm transverse strips, position resolution of ~ 1 -2 mm may be obtained. This becomes an important consideration when designing a device to separate π^0 's from single γ 's.

Often an electromagnetic calorimeter is called upon to help distinguish electrons from hadrons. Fig. 5 shows data from a study on how to get the best discrimination between π 's and e 's.⁽⁴⁾ The rejection ratio is shown as a function of the energy of the π/e for various minimum energies detected in the calorimeter. The dashed curves show the results using the calorimeter as a whole. An improvement can be obtained by making use of the fact that electrons start depositing energy immediately in a shower whereas even hadrons that deposit a lot of energy through an interaction are more unlikely to do so in the very beginning of the devices. The solid curves indicate the rejection ratios when the additional requirement is imposed of demanding 10% of the total energy in the first 2.57 radiation lengths. To obtain higher e/π rejection, calorimeters must be supplemented by other devices such as Cerenkov counters, transition radiation detectors, or measurements of dE/dx .

2. Hadronic Showers. In contrast to electromagnetic showers where the energy resolution is dominated by sampling statistics, there are many additional complications in hadronic showers. The relative importance of the various processes in a hadron shower in an iron-liquid argon device⁽⁶⁾ is shown in Fig. 6. The ionization is due to the energy detected from minimum ionizing particles in the shower. The electromagnetic component comes

from the production of π^0 's and is seen to increase in relative importance with energy. The nuclear reaction part arises from heavily ionizing fragments of the strong interactions of primary or secondary elementary particles in the shower. Liquid argon has a linear response even for these particles. Plastic scintillator saturates for such low energy particles, hence the use of plastic scintillator may lead to slightly worse energy resolution when compared to liquid argon. The dotted curves represent undetected energy in the shower due to binding energy, neutrinos and particle leakage through the boundaries of any finite calorimeter. It is this undetected energy which leads to the fact, shown in Fig. 7, that below $\sim 2 \text{ g/cm}^2$ per sample there is no improvement in the energy resolution.⁽¹⁾ In fact by selecting hadron showers that were primarily electromagnetic, Dishaw was able to show an improvement in the energy resolution.⁽⁷⁾ Fig. 8 contains a plot of the energy resolution versus the second moment of the longitudinal energy distribution. Events with a high second moment have a large amount of energy deposited in a small region - large electromagnetic component. The energy resolution improves by ~ 2 for less than 10% of the showers.

One way to improve the energy resolution of hadron calorimeters suggested by Willis is to use uranium instead of the much less expensive iron.⁽⁸⁾ Within the shower some of the particles cause U^{238} to fission which creates photons in the energy region of $\sim 1 \text{ MeV}$ which are detected. Therefore instead of exciting a nucleus which leads to undetected energy, slow neutrons captured in uranium and other losses previously called "binding energy losses" can lead to detected energy. The

results of tests using liquid argon sampling are shown in Fig. 9. At 10 GeV, hadrons in iron give $\sim 70\%$ of the signal obtained from 10 GeV electrons (or π^0 's). Using uranium boosts the hadron response while improving the energy resolution by almost a factor of two.

The energy resolution versus the number of interaction lengths of the hadron calorimeter is shown in Fig. 10. At 10 GeV, there is no improvement in the resolution for calorimeters more than ~ 5 interaction lengths.⁽⁸⁾ However, in designing calorimeters for higher energy machines, selecting the depth of the calorimeter is most critical. Higher energy showers require more absorption lengths but the cost of making a certain size calorimeter deeper can escalate quickly in a storage ring application. Another ameliorating consideration is that most jets fragment into mainly low energy particles - so if one is optimizing for jets the depth may not need to be as deep as if all the energy of the jet were in a single particle. It would be unfortunate if the gain in energy resolution due to using uranium were cancelled by having too shallow a calorimeter.

The transverse size of hadron showers was measured by Sessoms et al.⁽⁹⁾ and is shown in Fig. 11. Each of the histograms has a bin width of 2 cm and each plane is approximately one interaction length. Even though hadron showers are substantially wider than electromagnetic showers, there appears to be a narrow electromagnetic core to the average shower. Most hadron calorimeters have not been designed to have fine enough position resolution to be able to separate close hadronic showers. It is important to determine whether the study of the physics

of jets is aided by having a calorimeter of optimum position resolution.

The use of a calorimeter as a muon identifier is explored by considering the data of Fig. 12.⁽¹⁰⁾ Pions which do not interact, that is look like muons, fall off with the characteristic interaction length. Therefore a typical calorimeter of several interaction lengths can do a fairly good job of rejecting π 's. A muon passing through a calorimeter will give typically ~ 1 GeV of apparent energy. Therefore both momentum of the muon before entering the calorimeter as well as the position the muon has leaving the calorimeter must be measured in order to distinguish muons from the large number of low energy hadrons which would give a similar signal in the calorimeter.

Two practical considerations of the response of calorimeters in high rate environments is found in the data⁽⁷⁾ of Fig. 13 from Fermilab. The dashed histogram shows the response of the calorimeter to a low beam rate at 400 GeV. The solid histogram was measured at a high rate (300 kHz) and suffered from pileup from previous events and rate dependent gain variations in the photomultiplier tubes.

TYPICAL CALORIMETERS

For many years sampling calorimeters using scintillator used light guides to couple each layer of scintillator directly to the phototube. A particularly elegant example is the photon detector built by California Institute of Technology and used for a series of experiments at Fermilab.⁽¹¹⁾ The photon detector, a lead-scintillator-sandwich hodoscope

of 70 horizontal and 70 vertical counters, contains 19 radiation lengths of lead interleaved with long narrow ($73.5 \times 1.05 \text{ cm}^2$) scintillation rods. The horizontal and vertical rods sample alternate one radiation length lead sheets. Each counter optically joins 8 rods (either horizontal or vertical) to integrate the photon shower longitudinally. The device is homogeneous so the transverse position resolution of $\sim 2 \text{ mm}$ does not depend on where the photon shower originates.

A rather new development is the use of acrylic sheets doped with BBQ to replace the intricate and space consuming light guides of the previous example. The modules of Fig. 14 will be employed in the ISR in the Axial Field Spectrometer.⁽¹²⁾ The prototype uses $150 - 20 \times 120 \text{ cm}^2$ sheets of acrylic scintillator interleaved with 150 uranium plates 2 mm thick. The BBQ sheets integrate the showers longitudinally. The modules have separate readout for the left and right side of each $20 \times 20 \text{ cm}^2$ tower; and for the first 6 radiation lengths and the rest of the ~ 4 absorption lengths. The energy resolution for single charged hadrons is $35\%/\sqrt{E}$ with a position resolution (left to right) of $\sim 2 \text{ cm}$.

An example of using gas as a sampling medium is shown schematically in Fig. 15 in the design of modules for the MAC detector at PEP.⁽¹³⁾ D. Ritson discusses the physical principles of using proportional wire chambers in these lectures. Although the energy and position resolution of this device is $\sim 50\%$ worse than a scintillator-sampled detector, the proportional wire calorimeter has the advantage of much lower cost and greater ease of construction.

(2)

PROMISING NEW IDEAS IN CALORIMETRY

For the last year we have been trying to develop some new ideas in calorimetry for implementation at ISABELLE. Because the time to start construction of a detector is still a little bit off, we have been able to explore several ideas that seem promising, if somewhat speculative. Our goal is a finely segmented electromagnetic and hadronic calorimeter with excellent energy resolution that will operate in a magnetic field of ~ 0.5 Tesla. The next section will discuss the use of scintillators for sampling. The final section presents some new possibilities for gas sampling.

Apart from energy resolution there are a number of other considerations of particular importance to us in designing a calorimeter. They are segmentation and/or position resolution, operation in a magnetic field, cost and high rate capability. In particular, the problem of operating in a field of ~ 0.5 Tesla has led us to consider: 1) using solid state devices or micro-channel plate photomultipliers to measure the light in the field, or 2) using flexible light guides to ship the light to phototubes at a safe distance.

Solid state devices such as avalanche photodiodes (APD)⁽¹⁴⁾ or PIN diodes have high quantum efficiency ~ 0.8 and are relatively insensitive to magnetic fields. On the negative side these devices have low gain, small size and high cost. APD's which can operate at gains ~ 100 are limited to less than 3 mm diameter and have excess noise factors (8) considerably larger than photomultipliers. PIN's are cheaper and can have larger sensitive areas but are limited to unity gain. The energy

resolution expected from these devices is limited by the noise of the detector and its amplifier, and by their small size. Since the gain is small, one is dealing with small amounts of charge for each photoelectron. Thus one requires large number of photoelectrons to make the signal to be well separated from the pedestal σ_0 . The electronic noise of the σ_0 term in equation (1) contributes at a level which is largely determined by the device capacitance which is in turn proportional to the sensitive area. This minimization of photosensitive area runs counter to the need for high light yield mentioned above. Strand has shown that by cooling a 1 mm (3 mm) APD to -10°C the intrinsic noise of APD at a gain of ~ 100 is $\sim 3(7)$ photoelectrons rms. R. Boie⁽¹⁵⁾ suggests that an equivalent area PIN diode with a GaAs FET low noise amplifier with 100 nsec shaping time could be within a factor of 10 of this noise. To insure that a signal of 100 MeV is observable above noise in these devices requires σ_0 to be ~ 30 MeV. This implies a light yield then 330 photoelectrons per GeV for APD. Such light yields are not unreasonable for scintillator calorimeters, but are made difficult to obtain by the intrinsically small photo-sensitive area of these devices. For example, to match 1 cm strip scintillator elements and the 3 mm diameter APD, the BBQ rod would need to be 0.7 mm thick. To get efficient wave shifting in such thickness will require very high BBQ doping (~ 250 mg/l). The result is a wave shifter bar with very short attenuation length of its own light. An additional concern in the use of silicon detectors is their extreme sensitivity to charged particles. A single minimum ionizing particle traversing 100 μm of silicon will produce $\sim 10^4$ carriers.

Another approach to map a large area detector to a small photosensitive device that we have considered⁽¹⁶⁾ is shown in Figure 16. Here light from a scintillator without a secondary wave shifter is captured first in a POPOP doped rod in the same plane as the scintillator. Then the shower is integrated longitudinally by a BBQ doped rod running perpendicularly to the scintillator planes. The uniformity of this may be expected to be better than a design using only BBQ rods piercing the scintillator. The main problem here is to obtain enough light for reasonable scintillator thickness so that photon statistics make negligible contribution to calorimeter resolution. We have measured the feasibility of this method as shown in Figure 17. The requirement of 0.25 p.e./layer/minimum ionizing particle can be met with 3 mm of NE111. Two features of this design are notable: the POPOP rods capture light from a large solid angle and the narrowness of the scintillator strips makes the very short wavelengths accessible to the POPOP rod, thus increasing the light yield.

An other aspect of Figure 16 is the use of flexible light guides to bring the signals out of the strong magnetic field to normal phototubes. Since there has been such a revolution in the communications industry, naively one may think it would be easy to find a fiber optics array in this application. However, in the communications field one uses small aperture lasers to launch light so the photon budget is rather plush and whereas in a practical calorimeter the necessary aperture is at least $6\text{--}20\text{ mm}^2$. Table I gives the details of the attempts we have made to come up with a viable flexible light guide.

TABLE I.. Properties of Various Media for Flexible Light Guides

Material	Transmission	$\sim \left(\text{Numerical Aperture} \right)^2$	$\times \left(\text{Packing Fraction} \right)$	$\times \left(\text{Attenuation} \right)$ {2m} @500nm	Price	Radiation Hardness
Glass	1/8	$(0.50)^2$	0.75	0.6		$\sim 25 \frac{\text{db}}{\text{m} \cdot \text{krad}}$
Plastic PVT	1/35	$(0.46)^2$	0.60	0.23		$\sim 20 \frac{\text{db}}{\text{km} \cdot \text{krad}}$
Quartz	1/100	$(0.22)^2$	0.25	0.93	\$\$\$	$\sim 5 \frac{\text{db}}{\text{km} \cdot \text{krad}}$
Ce ⁺³ La doped glass	1/5	$(.5-.6)^2$	0.75+	0.76	\$10/m 3mm ϕ \$30/m 6mm ϕ	$\sim 10 \frac{\text{db}}{\text{km} \cdot \text{krad}}$

At first we tried a glass array. It has a large aperture and moderate attenuation properties. But normal glass is quite sensitive to radiation. We looked to plastic since most light guides are made of plastic if not normally flexible. We chose PVT instead of acrylic on the basis of radiation hardness. Since fibers must be coated, the numerical aperture (N.A.) of a clad fiber is always less than a normal light guide which has air interface. Also plastic is not very transparent. Quartz fibers seemed to have several desirable attributes. They are certainly the most transparent medium tested and are the most radiation hard. However, the index of refraction of quartz (~ 1.5) necessitates a thick silicone cladding which leads to a very low N.A., poor packing fraction and difficulty in assembling couplers. Also the extreme cost is a disadvantage. We have therefore come back to glass and are now in a contract with Galileo Electro Optics Corporation to produce a lanthanum trivalent-cerium doped boro silicate glass which on paper looks quite promising.

We have been watching closely the developments in microchannel plate photomultipliers. Recently Oba and Rehak⁽¹⁷⁾ have shown how to improve the lifetime of the device and have measured the response in a field up to 0.7 Tesla. Even at this field, as long as the field axis is mainly axial, there is only a small effect on the gain. Although many practical problems need to be solved and the current price is high, this device shows promise. One way to minimize the cost is to have many elements per microchannel plate. With a good system for obtaining the signal from segmented anodes while preserving the linear

response, one could imagine piping many separate signals to the face of one tube via fiber bundles.

If the devices are operated in the saturated mode in order to achieve a low excess noise factor, then there is a recovery time of at least $100 \mu\text{sec}(\tau)$ per microchannel for the best plate in existence. In calorimetry application where the average number of photoelectrons per event ($\bar{n}$) is large, one needs a large number of microchannels per element (N) in order to avoid gain sag at high event rates (F). We can express this requirement as $N \gg \bar{n} F \tau$. Since for existing microchannel plates $N \sim 10^4/\text{mm}^2$, the rate and light yield determine the necessary area per element for a multianode case. At ISABELLE we must be prepared to face rates of up to 10^5 GeV/sec/element. For a light yield of 200 p.e./GeV this would imply a surface area of $10 \text{ mm}^2/\text{channel}$. If microchannel plates could be made to saturate at lower gains, τ would be reduced.

Gas Sampling Calorimeters. Great advantage is to be gained with finely segmented calorimeters. Sampling, sufficiently fine to observe the shower shape not only improves position resolution but also greatly aids in particle identification. This is particularly true for neutral particle identification. Photons, neutral pions and eta mesons, cannot be distinguished at high energies by other means. Although ultimately limited by shower size, the resolving

power achieved in most experimental detectors is determined by size of the sampling elements. This in turn is limited by overall cost.

The much lower per channel costs of calorimeters employing gas sampling and amplification as compared to those using scintillator-photomultiplier combination makes them, in this regard, very attractive for use in large solid angle detectors. However, certain unfavorable characteristics associated with gas sampling calorimeters must either be accepted or overcome. These are listed below.

a. Loss of energy resolution: For a given average sampling, the energy resolution of gas calorimeters is about 50% worse than scintillator detectors (eg. at $1/2$ radiation length sampling in lead $\sigma \approx 18\%/\sqrt{E}$ for the gas device versus a typical $12\%/\sqrt{E}$ sampling with scintillator). Though the reason for this loss of resolution is not entirely clear, the situation can be improved by operating the gas calorimeter at high pressure. (18)

b. Slow response: The length of the electrical signal is primarily determined by three things - the charge collection time, the signal generation time or rise time, and the RC time of the detector/amplifier combination. Though a precise discussion is complex, two fundamental requirements for fast response are: small drift distances and small capacitance. These criteria are, however, difficult to meet and pulse lengths of more than 100 ns are typical. In addition, there is the problem of the extremely long tail generated by the slow moving ions that must be properly dealt with in high rate situations to minimize the effects of pileup.

c. Low density and difficult construction: The exponential dependence of the gas amplification on the field strength at the anode wire necessitates maintenance of strict tolerances upon all dimensions comprising the anode cathode geometry, in order to maintain uniform response. Practical tolerances lead to sampling layers that are thicker than those achievable with scintillator. For a given sampling, gas calorimeters are of lower average density than those using scintillator. The finer the sampling, the worse the discrepancy because the metal thickness becomes negligible compared to that of the gas. Since the shower size grows inversely to the density, this reduction in density can quickly obliterate the advantage to be gained through increased segmentation.

One other important consideration in evaluating the performance of calorimeters having fine segmentation in one-dimensional projections only is the degree of correlation between the energy measured for a given shower in each of the various projections. In designs providing only two projections, this is most critical because pulse-height matching between the two views is the only way to resolve ambiguities produced in multi-shower events. Clearly, devices in which the correspondence is exact, subject only to the limitations of electronic noise, are to be favored over simply interleaved views. The alternating samples make entirely independent measurements of the cascade with results differing according to sampling fluctuations. Detectors having projections, each of which samples a different part of the shower longitudinally, are of practically no use in complex events since the typically large variations in individual shower development can wipe out all pulse height correspondence between views, even to

the extent of losing one view entirely. There is, nevertheless, considerable advantage to having separated pairs of interleaved or corresponding views at various longitudinal levels. The best position resolution and resolving power are obtained by measuring only the early part of the shower, before it has grown too large. Multiple levels are necessary to obtain high efficiency for late developing showers.

We are developing a new construction technique which will allow the simple and low cost assembly of high performance gas calorimeters. We believe that a gas sampling calorimeter build in this way will provide performance equal, or superior, to scintillator or liquid argon calorimeters in all respects except energy resolution. It is hoped that the energy resolution will remain sufficiently good that the considerable cost advantage will make this type of detector a clear choice for most ISABELLE applications. A mixture of equal volumes metal or metal oxide powders with acrylic monomer produces a low viscosity slurry which may be poured into molds of any desired shape before polymerization. The volume ratio and viscosity are variable to a large extent, making it possible to obtain castings of good uniformity over a range of densities. At BNL, the Department of Energy and Environment originally developed this technique using sand and crushed stone in place of the metal powder in order to obtain a high strength product which became known as plastic concrete. DEE, at our request, has made sample polymerizations incorporating lead and lead oxide powders. In both cases density of more than half that of lead metal may be achieved. Although the lead oxide product has lower density, it is harder. Both plastic combinations are good insulators ($>10^{13}$ ohm-cm); however, the lead product has twice as high a dielectric constant ($\epsilon = 20$) and becomes suddenly and irreversibly conducting if a high enough field is

applied. In the case of PbO the final product has an approximate assay of 84% Pb, 6% O and 10% PMMA by weight.

We are presently preparing to cast the PbO plastic into sheets as shown in Figure 18. We will then plate the surface with conducting cathode strips running perpendicular to the grooves. After placing anode wires centered in the half cylindrical grooves, these plates may be stacked so the grooves are arranged in a close-packed hexagon. Alignment is easily maintained by sacrificing the end most groove to an alignment rod. We hope to find a private company to construct for all plate fabrication including plating. The molds used for making the sheets are actually themselves molded from a single machined metal plate having the same surface features as desired for the final product. In this way a high production rate for high tolerance final plates can be achieved.

The two projection readout with the beam in position (a) in Fig. 18 is obtained by joining rows of anode wires in one view and cathode strips in the other. Note that in this way the X and Y pulse height measurements are equivalent as they see exactly the same charge. In this design the largest capacitance around is that coupling adjacent cathode strips. We estimate this to be in the few hundred picofarad range. If we can keep this small enough we may be able to achieve pulse lengths dominated by the sum of the charge collection time ($1.5 \text{ mm} \times 20 \text{ ns/mm} = 30 \text{ ns}$) and the PWC rise time ($\sim 30 \text{ ns}$). Alternatively, the beam can be aimed at the device as indicated by (b) in Fig. 18. Then the cathode strips would integrate the shower longitudinally and could be arranged in towers. The

wires could be connected in bands of constant θ for a trigger proportional to the sum of the transverse momenta.

Note that for the dimensions shown in Figure 18, an initial PbO plastic density of 6 g/cc gives a final average density of 4 g/cc for the entire calorimeter. Monte Carlo (EGS) simulations of showers⁽¹⁹⁾ indicate that this sampling arrangement is probably equivalent to a layered sampling of a 3 mm gas and 5.7 mm PbO plastic. This is about 1/2 r.l. sampling. Comparing this to a Pb scintillator calorimeter having layers of 3 mm and two crossed scintillator layers of 3 mm thickness each, one finds similar average density. Of course, the density of the scintillator calorimeter can be raised by increasing the lead thickness to 6 mm while still obtaining energy resolution similar to the gas device. If wave length shifting techniques are used the signals would also be of similar length (~ 60 ns).

In conclusion we believe that with these techniques gas sampling calorimeters may be constructed that provide performance statistics sufficiently close to scintillator devices that cost considerations alone will indicate their use in most ISABELLE applications. As a final comment we list several other salient features of this technique:

- i) Materials other than PbO such as tungsten, iron, UO_2 , or iron oxide may be used as the basic material. Although all dimensions and performance statistics will change according to the material, there may be other useful applications of the plastic casting technique.
- ii) Uniformity is easier to obtain at edges than in the case of scintillator.

iii) Magnetic fields are of less concern than in the case of photomultiplier readout.

iv) Other casting techniques make the contemplation of non-planar structures appear reasonable.

One of the main problems of any calorimeter is fitting modules in a cylindrical or spherical geometry. This is because most designs use rectangular sheets. For an electromagnetic calorimeter with less than fifty samples, one can make each sheet of radiator and detector a slightly different size to fit into the desired geometry. However for a deep, fine sampled hadron calorimeter this quickly becomes overwhelming. One possibility is to use scintillating fibers as discussed by Borenstein et al.⁽¹⁴⁾ as a sampling medium in a solid cast of plastic loaded with heavy metals or metal oxide. The fibers could be wound like wires in a PWC on frames and put into a mold. This mold could have sloping sides necessary to be a section of a solid figure. Since the fibers are coated, the material surrounding it should not affect the light output. To check the feasibility of this approach we constructed a modest model. The fibers of 2 mm diameter of NE102 were arranged in a close packed hexagonal array with distance between centers of 3.3 mm and the surrounding glass tube was filled with a mixture containing PbO. A phototube was placed on the end and the device was brought to a test beam. The results are shown in Figure 19. Unfortunately the trigger counters had a larger sensitive area than this device. However, there is clear peak in the distribution of pulse heights from π^- passing through the device. Although the electron beam was not extremely cleanly defined,

there is evidence that the electrons give, on the average, larger pulse heights even though only part of a shower could be contained within this device. We imagine reading out the ends of the fibers parallel to the intersecting beams with waveshifter bars. However if a crinkle could be introduced in the fibers one could imagine arranging the fibers perpendicular to the beams and getting the light out of the back of the calorimeter with no shifting at all. Practicality questions abound: 1) what are the costs of this device; 2) how to make the mold release from the thousands of fiber ends; and 3) what are the variations in light output in various places in the solid.

We would also like to report on the idea of Polk, Smith and Willis⁽¹⁹⁾ to instrument the iron poles of a magnet with a gas sampling calorimeter. The goal is to have moderately good energy resolution for hadron and electromagnetic showers and have magnetic properties of ordinary steel. T. Ludlam, et al. has constructed, and is now testing, a device of this type. The holes in the iron are in the pattern of a quincunx, 2 mm x 5 mm, so that a charged particle will be detected in 25% of the layers on the average. Test data should be available soon.

Another new idea in gas sampling is being implemented by the LBL-TPC group⁽²⁰⁾ shown in Fig. 20. By stretching nylon monofilament at right angles to the sense wires, a gas calorimeter can be operated in a limited discharge (Geiger) mode. This improves the energy resolution by minimizing the Landau fluctuations of individual charged particles in the shower up to the energy where two particles are likely to be found in a single cell. Still low energy δ -rays which may set off many cells can be detrimental to the energy resolution. Fig. 21 shows

that the improvement in the energy resolution holds up to a certain energy where saturation occurs. This saturation means that it is likely for two electrons in the shower to be in the same cell. Another feature of this design are two sets of cathode strips at $\pm 60^\circ$ for each gap to allow excellent matching of showers.

Another new idea is the so called time projection calorimeter from Fischer and Ullaland⁽²¹⁾ at CERN. Variations on this theme have been suggested by W. Carrithers at LBL and L. Price at ANL. The idea is that particles would enter an active region of gas which is divided by an absorbing medium into cells as displayed in Fig. 22. The charge particles would drift down to a readout plane of proportional wires and crossed cathode planes. With sophisticated electronics recording both the time of arrival, the location and pulse height, the details of the shower can be reconstructed. A prototype has been tested with $\sim 34\%/E$ energy resolution. This technique does not have the advantage of high density or the ability to survive in a high rate environment.

This research was supported by the US Department of Energy under Contract No. DE-AC02-76CH00016.

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Fig. 1. Energy resolution versus number of radiation lengths per sample in electromagnetic calorimeters.

Fig. 2. Universal electromagnetic shower curve $v(\tau)$ vs. τ (see text).

Fig. 3. Energy resolution of electromagnetic showers versus depth sampled.

Fig. 4. Position resolution in electromagnetic showers for various energies and at various depths.

Fig. 5. Pion/electron rejection factors as a function of energy. Curves are given for several different values of the minimum energy required, $E_{\min}$. Solid curves give the results with more than 10% of energy in first 2.6 radiation lengths. Dashed curves show the rejection factors with no ratio cuts.

VARIOUS PROCESSES IN HADRON CALORIMETER

Fig. 6. Components of the hadron shower as a function of energy.

Fig. 7. Energy resolution of hadron showers for various energies as a function of the amount of material per sample in g/cm^2 .

Fig. 8. Energy resolution for different values of the second moment of the longitudinal energy distribution

Fig. 9. Energy detected in an iron and uranium-liquid argon detector for pions, electrons and protons.

protons 10 GeV/c

ENERGY RESOLUTION vs. LENGTH
Fabjan [FA77]

deep enough → saturation

Fig. 10. Hadron energy resolution as a function of number of interaction lengths sampled in an iron-liquid argon calorimeter.

Fig. 11. Transverse size of a typical 20 GeV hadron shower sampled at various depths in an iron liquid argon calorimeter.

Fig. 12. Pions that do not interact as a function of depth in a hadron calorimeter.

Fig. 13. High intensity measured energy before rate corrections (solid histogram) and low intensity measured energy (dashed histogram).

6 RAD. LENGTH ELECTROMAGNETIC
SHOWER READ OUT

4 ABSORPTION LENGTH HADRONIC
SHOWER READ OUT

Fig. 14. Plan of a uranium scintillator hadron calorimeter using BBQ sheets.

Fig. 15. Cross section showing internal detail of the modules. For the shower chamber, dimension "A" = 2.8 mm of typemetal (83% Pb, 12% Sb, 5% Sn), and "B" = "C" = 9.5 mm. For hadron calorimeter, "A" = 2.7 cm of steel, "B" = 1.75 cm, and "C" = 1.27 cm.

Fig. 16. Double waveshifting approach to calorimetry.

Fig. 17. Light received by Phillips XP2008 phototube in number of photoelectrons by double shifting when a minimum ionizing particle traverses a 3mm thick scintillator.

Fig. 18. Sheet of plastic loaded with heavy metal as model for construction of a calorimeter. Cross hatching indicates copper plating.

Fig. 19. Pulse height spectra for π^- and e^- traversing device.

Fig. 20. End on view of the PEP-4 semi-Geiger mode electromagnetic shower detector.

Fig. 21. Energy resolution for normal proportional mode calorimeters compared to a semi-Geiger mode device.

Fig. 22. Conceptual plan of the time projection calorimeter.