DREAMS AND SCHEMES -- or -- HADRON CALORIMETERS IN DESIGN

Bruce C. Brown
Physics Department, Fermilab*

I would like to follow the talks we have heard on results of measurements with calorimeters by discussing a few of the designs now being considered. I approach this from the position of an experimenter in the middle of the design of a new calorimeter. I will divide my time between some personal views on calorimeter design requirements and opportunities, and a presentation of some of the new designs under consideration or under construction for Fermilab experiments.

Purposes of Calorimeters

Of course, for any device the first crucial design question is to ask how is it to be used? I show in Table I a list of selected Fermilab experimental proposals which give examples of various uses of hadron calorimeters. Clearly such a wide variety of uses will call for a wide variety of designs.

A crucial early question in a calorimeter design is to decide whether it is to be used primarily as a triggering device or primarily as a precision analysis tool. Frequently a counter with

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less than ultimate resolution will provide useful triggering information but non-uniformities across the aperture will introduce unpleasant biases. For analysis purposes unequal responses can be corrected in software (to some level) while high resolution will typically be more crucial.

Design Considerations

At this point I will get to my list of design considerations shown in Table II. Some I will leave as obvious (meaning I do not know the problems) while others I will discuss in more detail, especially as the requirements interact with each other. I suspect there are two typical spots on this table to begin a design. One is item A. Energy Resolution and Energy Range. The principle options one has to consider are classified under Materials and Light (or Ionization) Sampling. We have heard discussions of several systems today and will hear about more systems tomorrow. But I suspect that the options are open for radically new materials and sampling techniques. As an example I will present later in the talk a design for a calorimeter with water as the interaction and detection medium. One particularly valuable option in shower sampling is available for analysis calorimeters. If the shower is not fully contained in the calorimeter, then <u>if</u> longitudinal samples of the shower development <u>are available</u>, an extrapolation procedure can be devised to estimate the energy leakage.

Although a few elite experimenters may begin a calorimeter design from purely physics considerations, I suspect that most experimenters begin as I did with the scale of their design efforts set by cost considerations. I discovered that a major portion of the costs were in detectors--digitizers, phototubes and bases, scintillator (if it was used) and (even) light guides. It was clear that an elegant solution to the sampling and light collection problem would possibly allow a detector priced within my budget which had good energy resolution. In exploring this I have found several interesting techniques that various people are using for light gathering schemes. Later today, Dr. Larry Sulak will present some techniques for packaging liquid scintillator for use in calorimeters. A Cal Tech group working on Experiment 111 have perfected techniques which allow them to get uniform pulse height response from a long thin plastic scintillator. Jeff Appel and Art Timm at Nevis Labs developed a very low cost high quality light guide fabrication scheme -- I call it wrinkled light guides. It gives nearly the uniformity of a twisted light pipe but with only the machining required to polish the edges of one sheet of lucite.

Wavelength Shifters

An important point in calorimetry design is that the shower process at high energies produces a large signal in any photon collecting device. It is then possible to throw away large amounts of light in order to obtain simple detectors and/or uniformity of response. This brings up the possibility of using wavelength shifter materials. These are fluorescent materials which absorb radiation in one wavelength band and re-emit it at some longer wavelength. They offer the possibility to:

1) Change the photon spectrum seen by the detector.
2) Change the phase space of the light to be detected by absorption of incident light and re-emission which is isotropic at the absorption center.

A substantial literature exists using feature 2 for light gathering schemes.[1-7] In recent years practical materials have become commercially available. Figure 1 reproduces an absorption and emission spectrum for Bis-MSB which is the main active component in the Pilot 425 detector material available from Nuclear Enterprises.[8] But I would like to add that the source of that curve, a book by Berlman,[9] lists a large number of other fluorescent materials which could potentially be useful for light gathering schemes. I also show in Fig. 1 a graph from the very interesting article by Keil[4] showing the absorption and emission spectra of some commercially available fluors. I note that Green 740 has properties suitable for use with phototubes which might be particularly applicable for light gathering schemes. One might hope that sophisticated systems based on wavelength shifters may prove to be practical in the future.

My last general comment before I move to discussion of some specific detectors concerns phototubes. We are just getting fully into an era when high energy physics is (ägain?) asking for precision, high rate analog measurements with phototubes. Several groups are simultaneously discovering a whole host of problems. The requirements are generally for high rate capability, modest to high gain, and a large linear dynamic range. And most importantly we want this with a stable gain -- stable against rate dependences and stable enough against long term drift to allow calibration intervals to be reasonable. Later today Cordon Kerns will discuss this problem. He will present techniques and results obtained while seeking to satisfy the requirements for phototubes to be used by the experimenters in E236 and in E288. Fred Murphy of UCSB (E25) and Alvin Tollestrup of Cal Tech (E111/268) have also recently presented results on phototube stability tests.[10]

Next, I would like to discuss a few experimental designs which seek to go at least one step beyond existing designs toward a more sophisticated calorimeter technology. I will begin with Fig. 2 which shows a steel-liquid scintillator calorimeter used in the beam in Quark Search Experiment 75.[11] It is shown as an example of the simplicity one can achieve when objectives are limited. It is able to measure a shower with a single phototube and no light guide.

I would next like to discuss briefly the calorimeter being designed for Hadron Jet #246. I will not give a real description of the device, since Dr. Selove will be presenting a paper on it in the session tomorrow, however, I would like to present Table IIIa in which some of the interesting design features of the detector are shown.

In the calorimeter being built for E236, the calorimetry technique is not particularly new, but rather the new feature is the attempt to obtain position information in the calorimeter both for analysis and in a fashion such as to allow a useful fast trigger on transverse momentum (transverse energy). Table IIIb lists major features of the calorimeter as described by the experimenters[12] while Fig. 3 shows diagrams of the detector and Fig. 4 shows the experimental layout.

Particle Search Experiment #379 proposes to use a calorimeter in a search for hadronically produced μ and ν final states. The proposed calorimeter has several interesting features. Table IIIc shows some of these features as described in the experimental proposal.[13] Figure 5 shows the proposed layout for the experiment. I would like to emphasize that the proposed design is interesting in the degree to which they plan to contain the shower and the technique they propose to control leakage losses by segmenting the calorimeter and looking for energy deposition in the sides and back.

The final calorimeter design I will describe is the one I am working on for Di Lepton Experiment #288. I began the design effort after having a few months experience with the lead glass calorimeter in Experiment #70 and had acquired an appreciation for the ease of using a total absorption device. Although I saw no way to efficiently look at segments of the shower in the way we did with lead glass, I realized that the directionality of Cerenkov light might allow a relatively simple light gathering scheme for a total absorption counter. The experimental requirements and some of the design features are shown in Table IIId and a sketch of the proposed design is shown in Fig. 6. I will use water both as an interaction medium and as a detection medium for the production of Cerenkov light. The light is transmitted at about 41° from the beam direction but by using mirrors along the side of the box the signal will all (except for effects of light absorption in water) reach the end opposite the beam entrance aperture. There a set of wavelength shifter panels (Pilot 425) are inserted into the water to absorb the Cerenkov radiation. Since the acrylic plastic has a higher index of refraction than the water a fraction of the remitted light will be light piped along the detector to a standard light pipe-phototube detector system.

At this time the idea is essentially ready for the engineering design. A test of the light gathering scheme and of the shower properties has been carried out with a small test apparatus. I hope to have the device ready for beam testing by early fall.

Closing Remarks

Before closing I would like to state a few of the general questions which plague a calorimeter designer and hope that they will receive some attention either theoretical, calculational, or experimental. I would emphasize that the answers need to be presented not only for the experimenter who is seeking to design the ultimate resolution device but they need to allow reasonable design choices even for low resolution devices when space, aperture, simplicity, and cost create compromises.

Some General Questions for Calorimeter Design

1) What kind of general statements can be made about energy sampled (lost) vs. resolution? Alternatively what are specific effects of
   a) sampling (uniform or optomized) vs. total absorption
   b) ionization vs. scintillation vs. Cerenkov light vs. whatever energy sampling scheme.
   c) shower leakage - lateral and longitudinal
   d) how much development information is useful in order to extrapolate when there is leakage?

2) What do the high energy (low energy) tails look like in detail? How are they affected by the resolution questions in (1)? Need information out to 10^{-3} or 10^{-4} level.

3) Shower development - need good description for designs
   a) material independent formulas and/or rules-of-thumb- especially for shower containment but also for uniformity and sampling optomization studies.
   b) Some guidelines on how good a Monte-Carlo one needs to achieve desired results at any level.

REFERENCES

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[9]Isadore B. Berlman, Handbook of Fluorescence Spectra of Aromatic Molecules, Second Edition, Academic Press, New York, 1971. (Note that the second edition is greatly expanded over the first.)

[10]Private Communication, Fermilab Research Technique Seminar.

[11]T. White, Internal Memo (unpublished) and T. Nash, et. al., Phys. Rev. Letters 32, 858 (1974).

[12]Peter Limon, Private communication.

[13]Fermilab Proposal #379.

TABLE I

Examples of Uses of Hadron Calorimeters

1. Neutral Particle Detection

   Neutron Elastic Scattering #248

   Particle Search #330

2. Measurement of Total Hadronic Energy

   A. Measure Total Energy in Neutral Particle Induced Event

   Neutron Cross Section #4

   Photoproduction #87A

   B. Measure Hadronic Energy accompanying μ or ν final State

   ν target { Neutrino #1A, Neutrino #21, Neutrino #256, Neutrino #316 }

   μ target { Muon #26, Muon #203A }

   Hadron target - Particle Search #379

3. Identify Particle Type (Electron-Hadron-Muon)

   Lepton #70 (DiLepton #288)

   Elastic Scattering #69

   Particle Search #100

4. Select Events according to Energy Deposit in a Given Solid Angle

   A. High $p_\perp$ Trigger

   Hadron Jets #236

   Hadron Jets #246

   Hadron Jets #260

   B. High Mass Pair

   DiLepton #288

TABLE II

Design Considerations for Hadron Calorimeters

PHYSICS

- A. Energy Resolution and Energy Range
- B. Spatial Resolution
  1. Angular Resolution
  2. Multiparticle Separation
- C. Timing Resolution and Rate Capabilities

EXPERIMENT DETAILS

- D. Calibration
- E. Data Handling Requirements
- F. Physical Size
- G. Cost - Effort and Dollars
  Design, Fabrication, Operation

CALORIMETER DETAILS

- H. Materials
  1. Interaction Medium
  2. Detector Medium
  3. Detector
- I. Light (or Ionization) Sampling
  1. Frequency of Sampling-Uniform or Optomized
  2. Integrate along Shower in
     Detector <u>or</u> Electronics <u>or</u> Software
  3. Light Guide & Phototube Requirements
  4. Special Techniques
     - a. Wavelength Shifter Materials
     - b. Wrapping of Scintillators for
       Uniform Pulse Height Response
     - c. Liquid Scintillator Techniques
- J. Phototube Selection

TABLE IIIa

Hadron Jet #246

Physics Features	1.	Position Resolution
	2.	Multiparticle Capabilities
	3.	Good Energy Resolution in Low Energy Region
Calorimetry Features	4.	Steel and Liquid Scintillator Detection Medium
	5.	Detectors using Wavelength Shifter in Lucite for Light Collection
	6.	Modular Design

TABLE IIIb

Hadron Jet #236

Physics Features

1. Position Resolution
2. Good Energy Resolution
3. Large Solid Angle (~ 3 str in CM) but Modest Size

Calorimetry Features

4. "Standard" Plastic Scintillator Sandwich with lead then steel absorber.
5. Integrate Along Shower with Light Pipes - separately for Electromagnetic and Hadronic Component.

Area:	20" wide x 40" high (Front) 30" wide x 40" high (Back)
Position:	~ 100" From Target
Angular Acceptance:	6.75" radius hole will define ≈ 60-70 mr. cutoff
Total Depth:	~ 5.5 int. lengths.
Detector Material:	1/4" Pilot Y
Position Resolution:	~ 4" Vertical ~ 3 1/3" Horizontal (Counter Size)
Status:	To Be fully Operational Fall 1975

	Electromagnetic Detector	Hadronic Detector
Interaction Medium	Lead	Iron
Depth	2 1/2"	32"
Sampling Interval	1/4"	1"
Total Samples: Horizontal -	4 layers x 10 strips	16 layers x 10 strips
Vertical -	4 layers x 6 strips	16 layers x 6 strips

TABLE IIIb

(continuted)

Total of 32 phototubes to digitize

Two modes of Operation

1) Trigger on Hadron Calorimeter
   Using (mostly) horizontal Counters
   Analyze Spectrometer plus Calorimeter

2) Trigger on high $p_\perp$ single particle
   in spectrometer and analyze calorimeter

Can add downstream calorimeter to improve longitudinal containment.

TABLE IIIc

Particle Search # 379

Calorimeter Features (from P. 7 of Proposal)

a) Large enough transverse and longitudinal dimensions so as to practically eliminate energy leakage.

b) sufficient segmentation so that one would know if an anomalously large amount of energy were deposited near the edges.

c) high density, so as to minimize number of π and K decays

d) long radiation length so as to minimize Coulomb scattering

e) frequent enough sampling to obtain the best possible energy measurement.

f) ability to change the mean density in the front end to calibrate the number of π and K decays.

Design Resolution: 8 - 10% FWHM at 400 GeV

Eliminate Tails on Resolution Function

1. Provide for good containment (need only very small fiducial volume $\simeq$ beam spot size)

2. Segment calorimeter to allow for observation of energy distribution - can cut if energy is too close to edge.

TABLE IIIc

(continued)

Design (from proposal)

Make 3 layers of calorimeter:

I. 4 absorption length depth instrumented for precision measurement.

Front Face	40 x 40 cm^2
Material	Copper (~ 60 cm)
Sampling	Every ~ 2 rad. lengths (2.9 cm)
Detector	1/8" Scintillator

Total ≈ 20 detectors.

II. 6 absorption lengths

Front Face	70 x 70 cm^2
Material	Fe (~ 1 m)
Sampling	Every 3 rad. lengths (5.3 cm)
Detector	1/8" Scintillator

Total ≈ 20 detectors.

III. 6 absorption lengths

Front Face	1 m x 1 m
Material	Fe (~ 1 m)
Sampling	Every 6 r. l. (4" or 10.16 cm)

Total ≈ 10 detectors.

So total detector ≈ 16 absorption lengths. Also add wide angle energy measurement and muon catcher.

TABLE IIId

Di Lepton #288

Physics Features	1.	Good μ/hadron separation
	2.	Large Aperture
	3.	Modest Resolution but Good Uniformity for Triggering
	4.	High Rate Capabilities
	5.	Prompt Trigger Information Required
Calorimetry Features	6.	Simplicity of Fabrication and Use
	7.	Total Absorption - No Sampling Limitations
	8.	Muon Calibration with Minimum Effort
	9.	Minimum Number of Phototubes to Calibrate, Digitize, etc.

Interaction Medium:	Water
Sampling Technique:	Detect Cerenkov Light
Detector:	Wave Length Shifter in Lucite (Pilot 425) attached to Phototube
Aperture:	3' x 6' (each arm)
Interaction Depth:	6 Absorption Lengths (+ 1 1/2 abs. lengths of Pb Glass) = 16' of water

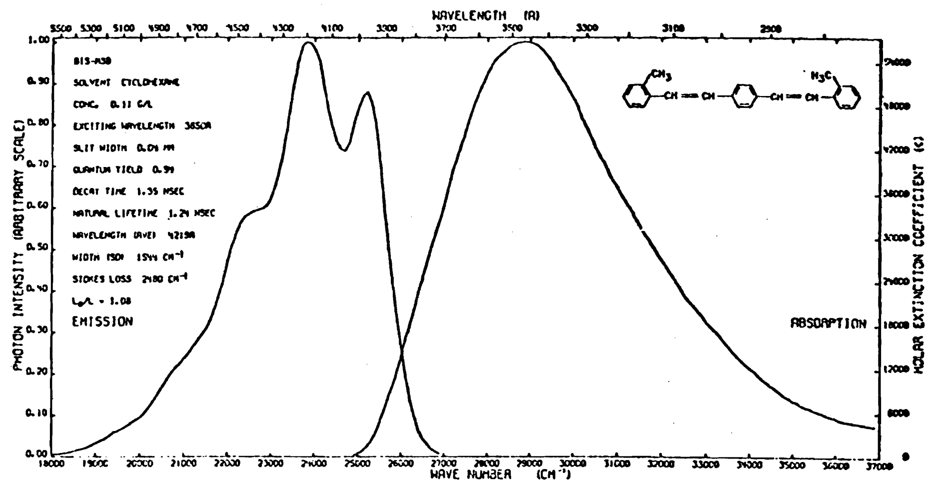


FIGURE 1a Emission and Absorption Spectra for Bis-MSB

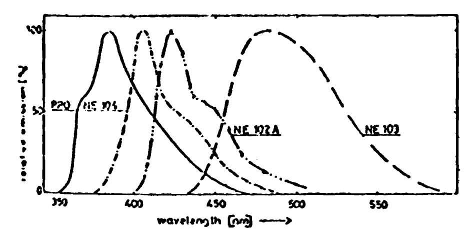


Fig. 18. Emission spectra of some organic scintillators.

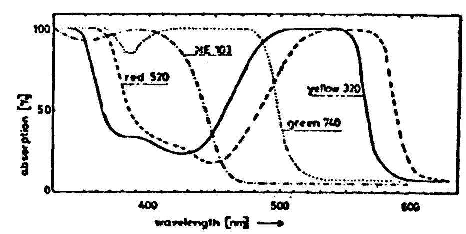


Fig. 20. Absorption spectra of some fluorescent materials.

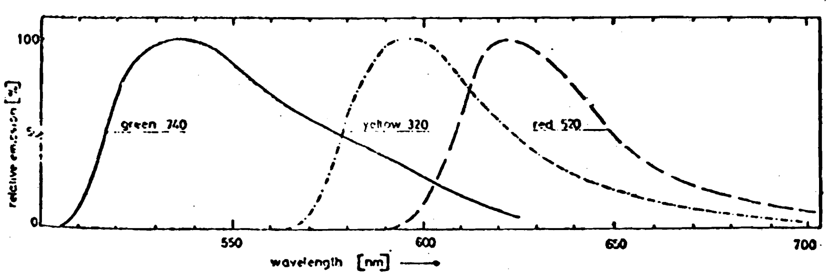


Fig. 19. Emission spectra of fluorescent acrylic glasses (Röhm and Haas).

FIGURE 1b Emission and Absorption Spectra of Some Acrylic Glasses

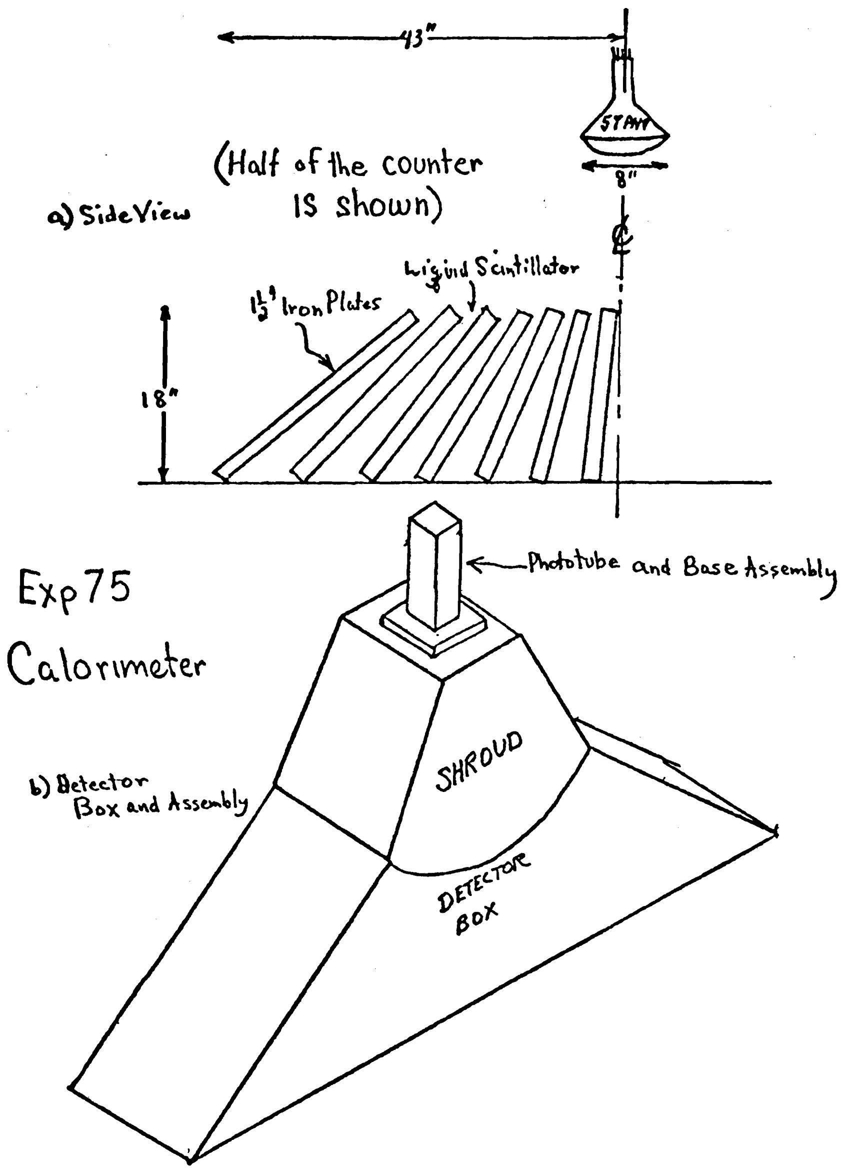
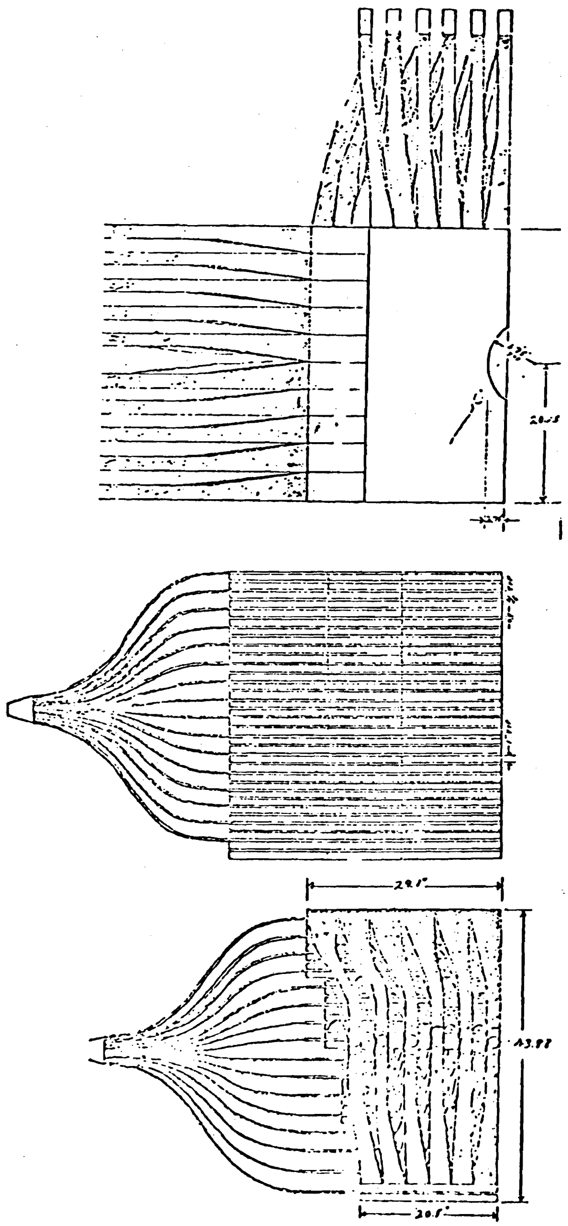


FIGURE 2 Hadron Calorimeter Design - Exp. Quark 75



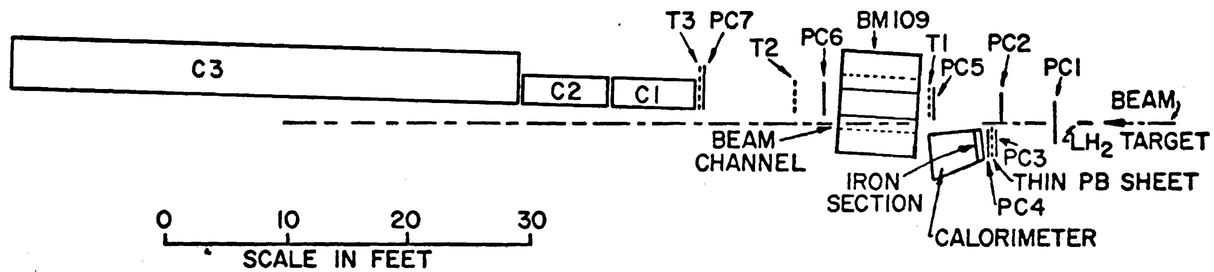
FRONT VIEW

SIDE VIEW

TOP VIEW

FIGURE 3 Hadron Calorimeter for Exp. Hadron Jet 236

CONFIGURATION OF APPARATUS E236



T1–3 TRIGGER HODOSCOPES

PC1–7 MULTIWIRE PROPORTIONAL CHAMBER SETS (X, U and Y PLANES)

C1–3 CERENKOV COUNTERS

FIG. 4

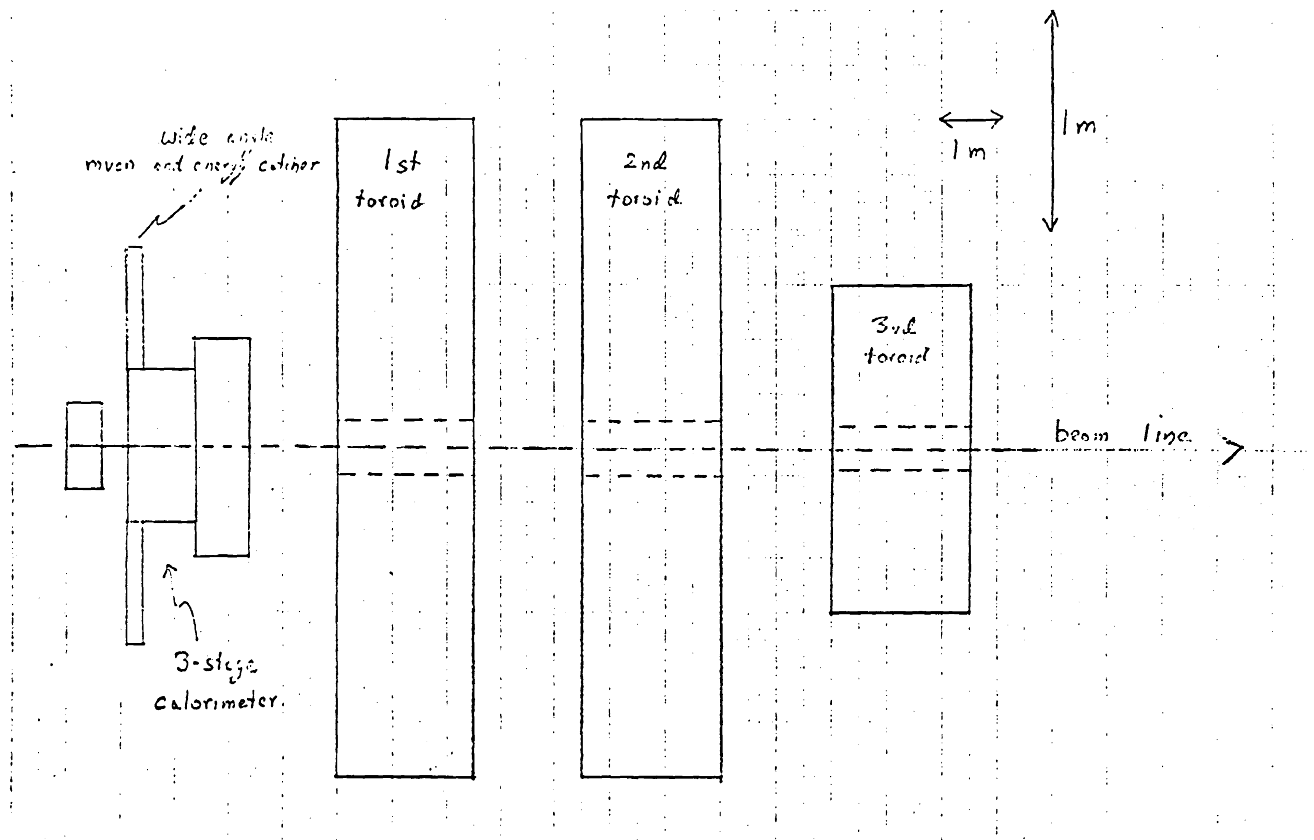


FIGURE 5 Schematic of E379 apparatus (detectors between toroids not shown).

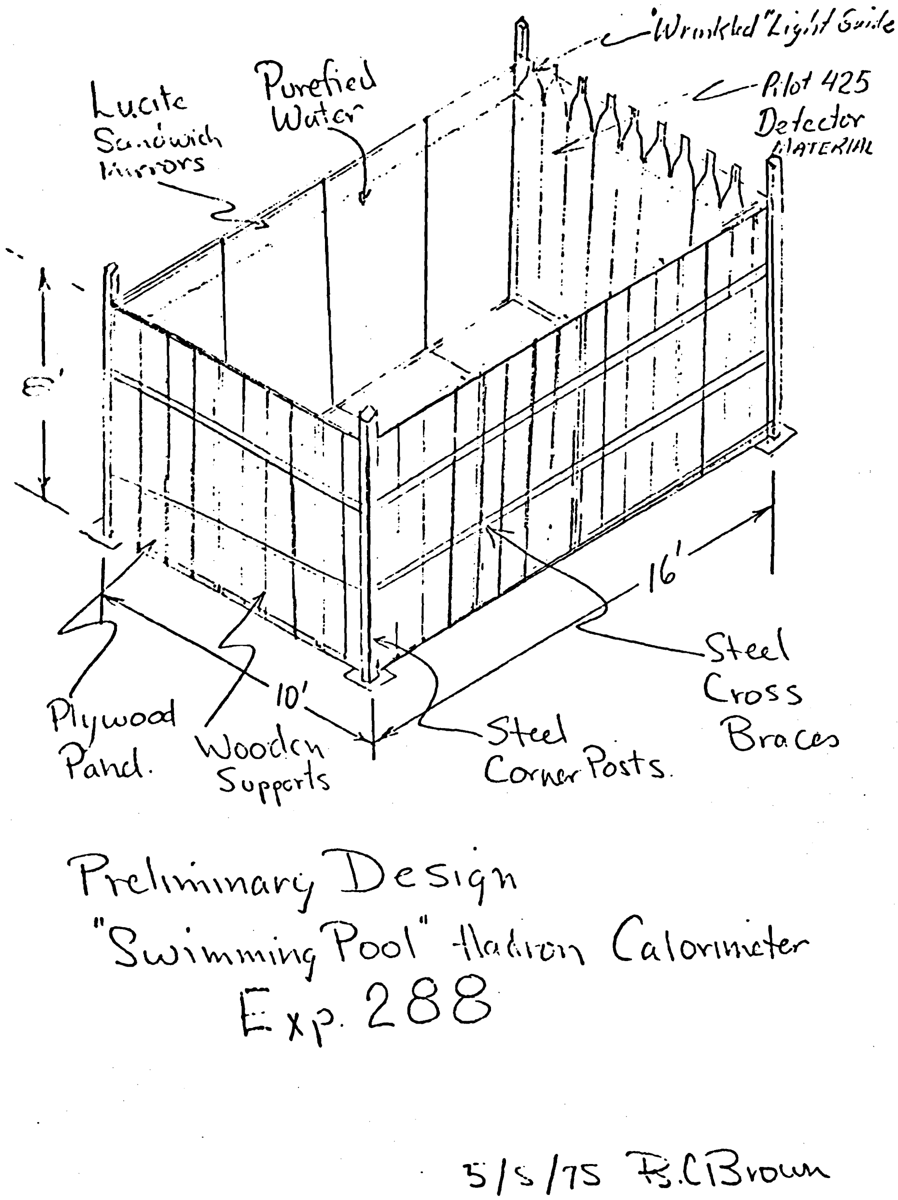

"Wrinkled" Light Guide
Pilot 425 Detector MATERIAL
Lucite Sandwich Mirrors
Purefied Water
8'
16'
10'
Steel Cross Braces
Plywood Panel.
Wooden Supports
Steel Corner Posts.
Preliminary Design
"Swimming Pool" Hadron Calorimeter
Exp. 288
5/5/75 R.C.Brown

FIGURE 6