SOME PHOTON AND NEUTRON CALORIMETERS FOR FNAL EXPERIMENT 87

J. Knauer, D. Yount

University of Hawaii, Honolulu, Hawaii[+]

B. Knapp, W. Lee, P. Leung, S. D. Smith, A. Wijangco

Columbia University, New York, N. Y.[*]

D. Nease

Cornell University, Ithaca, New York[*]

J. Bronstein, R. Coleman, L. Cormell, G. Gladding,
M. Gormley, R. Messner, T. O'Halloran,
J. Sarracino, A. Wattenberg, D. Wheeler

University of Illinois, Urbana, Illinois[+]

M. Binkley, R. Orr, J. Peoples, L. Read

Fermi National Accelerator Laboratory, Batavia, Illinois[+]

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ABSTRACT

Specifications and test data are given for three types of calorimeters used to detect beam photons and neutrons in FNAL Experiment 87. These are: (1) a high-precision ionization quantameter, (2) a lead-scintillator electromagnetic shower counter, and (3) an iron-scintillator hadron cascade detector.

I. INTRODUCTION

The neutral beam in FNAL Experiment 87 is produced by extracted protons that are incident on a beryllium target. The neutron component results mainly from primary proton interactions, while the photons are created by neutral-pion decay. The ratio of neutrons to photons is controlled by selectively attenuating the unwanted component. With 6 radiation lengths of lead, one obtains a relatively pure neutron beam, whereas 34 meters of liquid deuterium suffice to purify the photon beam. The intensities and energy spectra of the transmitted photons and neutrons are monitored by the quantameter, shower counter, and hadron detector described below, as well as by other well-known devices such as a pair spectrometer, secondary emission monitors, etc. The three calorimeters are of particular interest mainly because they have operated successfully in the new energy range made accessible by Fermi Lab.

II. THE FNAL QUANTAMETER

The FNAL quantameter is shown schematically in Fig. 1. It has been described in detail elsewhere,[1] and we give here only the salient features. Internally, the quantameter consists essentially of 44 coaxial copper discs, each of about 1 cm thickness. The spacing between discs follows Simpson's rule and averages about 0.5 cm. Compensation[2] for longitudinal shower penetration is obtained by making the last two gaps oversize, while compensation for radial shower penetration is achieved by using collector and high-voltage plates of different radii, respectively, 20.3 and 23.1 cm. The gain per GeV is expected to be independent of photon beam energy from 1 to 1000 GeV and to be independent of beam intensity for any practical photon flux that can be produced at FNAL during a uniform spill of 1 s duration. Measurements of the quantameter gain with incident electrons at SLAC yielded (416.0 ± 0.8) ions/GeV at 10 GeV and

(416.1 ± 0.8) ions/GeV at 19.7 GeV for a hydrogen filling, corrected to a standard pressure of 30.00 inches of Hg and temperature of 300°K. The gain was independent of intensity up to about 3×10^7 electrons per cm^2 per 1.5 μs pulse at 10 GeV, and it varied with beam centering by less than 0.1% over a 20-cm diameter. The quantameter has been in routine operation at FNAL for nearly two years and is used both as an absolute monitor of the total incident photon beam energy and as a relative monitor of the incident neutron flux.

III. THE UNIVERSITY OF HAWAII SHOWER COUNTER

The Hawaii shower counter is shown in Fig. 2. The active volume consists of 16 lead absorbers 0.936 cm thick, interleaved with 16 sheets of plastic scintillator 0.64 cm thick. The sensitive area perpendicular to the beam axis is nominally 30 cm x 30 cm. Light is collected on two opposing sides and is transmitted quasi-adiabatically through polished lucite. Finally, the light is mixed in lucite couplers mounted on two Amperex 60AVP photomultipliers to reduce the effects of any non-uniformity of the 20-cm-diameter photocathodes. The photomultipliers have 12 stages, but at FNAL energies, typically only the first 9 are used.

The two large photomultipliers permit exceptional shower counter uniformity. This was tested by moving the counter vertically and horizontally perpendicular to a pencil electron beam at SLAC. Uniformity data were obtained at both 5 and 15 GeV and were virtually independent of energy as expected from shower theory.[3] For vertical displacements up to ± 12.5 cm, there was no systematic change in either photomultiplier output. For horizontal displacements of up to ± 12.5 cm, the individual outputs decreased with increasing distance to the beam by about 0.8% per cm. The electronic sum of the two outputs showed no systematic variation over a 25 cm x 25 cm grid with rms fluctuations of ± 1.4%.

The calculated energy losses due to shower penetration[3] were 1.3% at 50 GeV, 2.3% at 100 GeV, 2.9% at 150 GeV, and 4.1% at 250 GeV. The effect of these losses can be seen in Fig. 3, where we have plotted shower counter pulse height summed over the two photomultipliers versus the incident photon energy in GeV. The photon energy was measured with a pair spectrometer upstream of the shower counter, and the resulting positron and electron tracks were both required to be within 5 cm of the counter axis. The vertical error bars of typically ± 1% were found by taking the square root of the number of pairs at a given energy. The horizontal scale was determined from the magnet field setting, which was linear to ± 0.3%. Within these uncertainties, the corrected and summed shower counter output is linear in energy up to 250 GeV. Gain versus energy was studied in the range from 3 to 15 GeV with the pencil electron beam at SLAC and was found to be linear to about ± 3% with negligible losses due to shower penetration.

The energy resolution of the Hawaii shower counter was measured at SLAC with a pencil electron beam of 3, 5, 12, and 15 GeV. The momentum acceptance of the beam was 3.5% FWHM (full width at half maximum). The counter resolution with beam momentum acceptance unfolded could be parameterized by the expression

$$\mathrm{FWHM} = 40\%/E^{1/2}, \tag{1}$$

where E is the incident energy in GeV. Additional measurements were made at FNAL with the M1 beam line set for negative particles of 50 GeV/c and a momentum acceptance of 4% FWHM. The beam itself consisted almost entirely of pions, and we therefore used transition radiation monitors from FNAL Experiments 229 and 261 to enhance the electron component in our trigger. A typical pulse height spectrum obtained with this trigger is shown in Fig. 4. The electron peak has a raw width of 7.5% FWHM, which yields an unfolded width of

$$\mathrm{FWHM} = 6.3\% \text{ at } 50 \text{ GeV}. \tag{2}$$

This is in reasonable agreement with Eq. 1, which gives about 5.6% at 50 GeV.

The energy resolution of a shower counter is normally dominated by fluctuations in the number of shower tracks sampled. The number of tracks above 1.5 MeV can be estimated from[3,4]

$$N_{\mathrm{tracks}} = 50\ E/t, \tag{3}$$

where t is the thickness of the lead plates in radiation lengths and E is again the incident energy in GeV. The predicted resolution for the Hawaii shower counter (t = 1.66 radiation lengths) is[4]

$$\mathrm{FWHM} = 2 \times 1.175/(N_{\mathrm{tracks}})^{1/2} \tag{4}$$

$$= 42.8\%/E^{1/2}, \tag{5}$$

which is similar to the experimental values given by Eqs. 1 and 2. The design parameters, operating procedures, and test data for the University of Hawaii shower counter will be described in more detail in a future report.[5]

IV. THE FNAL EXPERIMENT 87 HADRON CALORIMETERS

FNAL Experiment 87 has the capability of identifying and measuring the energies of various types of final-state particles, including neutrons. Neutral hadron energies are determined mainly by an array of iron-scintillator calorimeters consisting presently of a single plane and ultimately of two planes.

There are ten calorimeters in each plane: Eight are of the type shown in Fig. 5, and two are somewhat smaller, the 46-cm dimension being reduced to 15 cm. (The two smaller counters are used on either side of the beam at beam elevation.) Calorimeters of the larger type are also used, either side-by-side or two-deep, in studying the properties of the neutron and photon beams.

The active volume of the counter shown in Fig. 5 is defined by 12 iron blocks 5 cm thick, interspaced with 12 sheets of plastic scintillator 0.64 cm thick. The sensitive area perpendicular to the beam is 46 cm high and 84 cm wide. Light is transmitted through polished lucite to a single 58AVP photomultiplier having an 11-cm-diameter photocathode. Typically only the first 9 stages of this 14-stage phototube are used.

The uniformity and resolution of two of the larger calorimeters were studied with the M1 beam line at FNAL set for negative particles of 50 GeV/c and a momentum acceptance of 4% FWHM. For these tests the transition radiation monitors were not used, and the trigger consisted almost entirely of negative pions, for which edge effects were quite large. Furthermore, the beam envelope was determined by a scintillation counter 5 cm x 5 cm in area so that the geometric resolution used in the uniformity test was relatively crude.

The results of the uniformity test may be summarized as follows:

(1) The pulse height decreases by about 0.14% per cm as the beam moves along the center of the counter and away from the photomultiplier.

(2) The pulse height is 6% below the values on the median line when the beam envelope is centered 5 cm from the upper or lower edge.

(3) The pulse height is 30% to 50% below the values on the median line when the beam envelope is centered 3 cm from the upper or lower edge and 70% low in the corners 3 cm away from the edge farthest from the photomultiplier.

It was not determined what fraction of the losses at the edges could be recovered by adjacent calorimeters.

Fig. 6a gives the pulse height distribution obtained with 50 GeV/c pions incident on two successive calorimeters of the type shown in Fig. 5. Fig. 6b is the contribution of the downstream counter, and Fig. 6c is the pulse height distribution of the upstream counter. The energy resolution for a single counter (Fig. 6c) is 58% FWHM, while the combination of two counters in series (Fig. 6a) yields 39% FWHM. It should also be noted that the maximum of the single-counter distribution (Fig. 6c) lies about 19.5% lower than the peak for the combination (Fig. 6a). Evidently there is a significant loss of energy when only one calorimater is used, and fluctuations in these losses broaden the resolution.

The maximum of the pulse height distribution obtained with pions incident on two calorimeters (Fig. 6a) is (62.5 ± 2.3) times that found with 50 GeV/c muons traversing a single calorimeter. Assuming such a muon makes 12 tracks (one per scintillator), we obtain for the stopping pion an average of (750 ± 28) tracks at 50 GeV/c. Fluctuations in this number of tracks would contribute about 8.7% FWHM to the resolution: Evidently the 39% FWHM of Fig. 6a is dominated by factors other than the sampling thickness.

REFERENCES

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3. U. Völkel, DESY Report 65/6 (July 1965). See also H. Nagel, Z. Physik 186, 319 (1965).
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5. J. P. Knauer and E. E. Yount, A Shower Counter for FNAL Experiment 87 (to be published).

FIGURE CAPTIONS

1. Schematic diagram of the FNAL quantameter. Numbered arrows refer to: (1) housing, (2) one of the 22 large discs, (3) one of the 22 small discs, (4) copper screen, (5) front cover, (6) rear cover, (7) large compensation plate, (8) small compensation plate, (9) window flange, (10) one of the six tie rods, (11) bushing, (12) bushing spacer, (13) plate spacer, (14) washer.
2. University of Hawaii lead-scintillator shower counter.
3. Shower counter pulse height versus incident photon energy determined by a pair spectrometer. Corrections for shower penetration losses were made by moving the uncorrected points to higher photon energies.
4. Pulse height spectrum obtained with the University of Hawaii shower counter in a 50 GeV/c negative beam. The sharp peak results from beam electrons, while the remaining pulses are due mainly to negative pions.
5. FNAL Experiment 87 iron-scintillator hadron calorimeter.
6. Pulse height distributions obtained with incident pions of 50 GeV/c from: (a) two hadron calorimeters in series, (b) the downstream calorimeter alone, and (c) the upstream calorimeter alone.

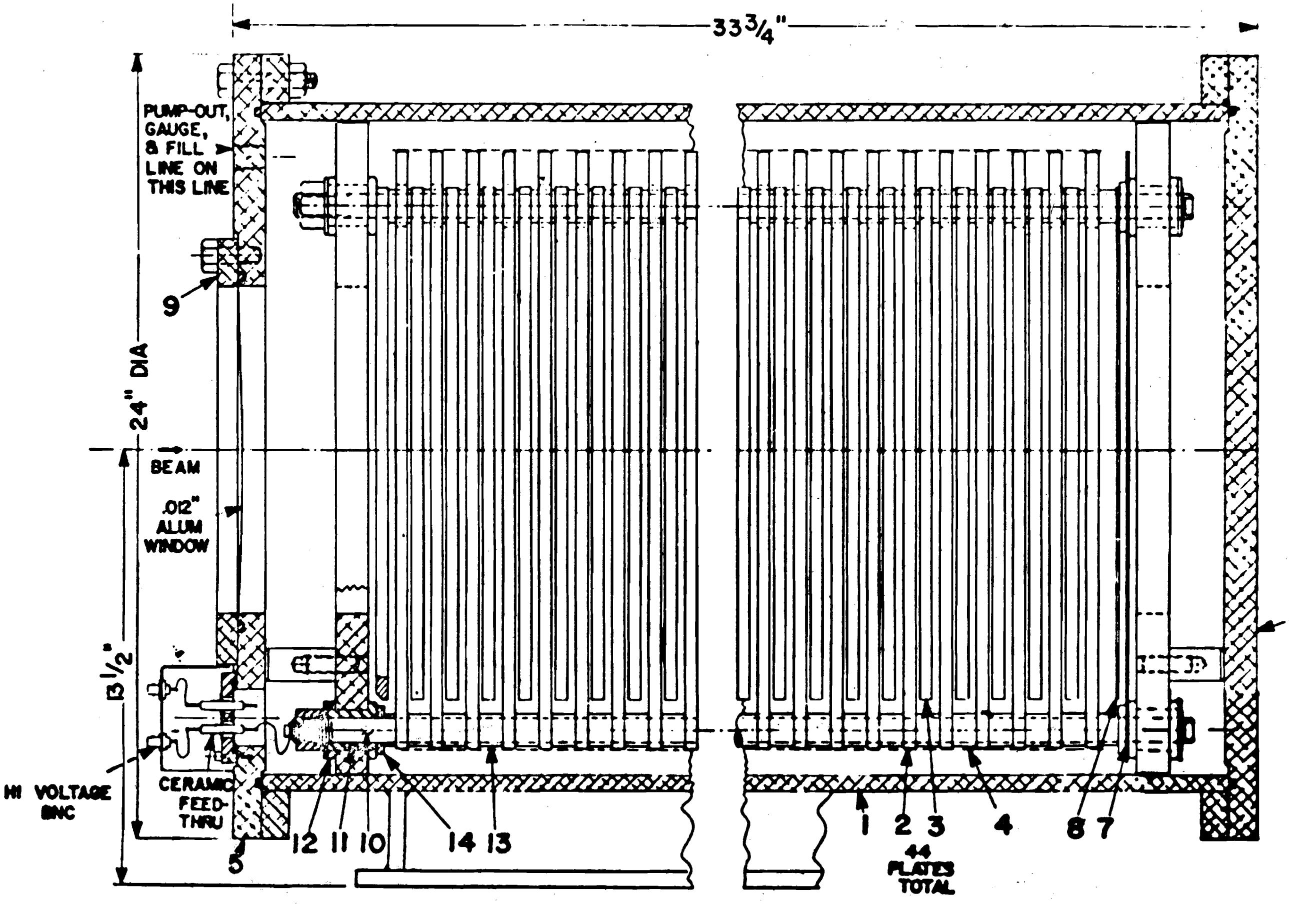
33 3/4"
PUMP-OUT, GAUGE, & FILL LINE ON THIS LINE
9
24" DIA
BEAM
.012" ALUM WINDOW
13 1/2"
HI VOLTAGE BNC
CERAMIC FEED-THRU
5
12
11
10
14
13
1
2
3
4
8
7
6
44 PLATES TOTAL

Fig. 1

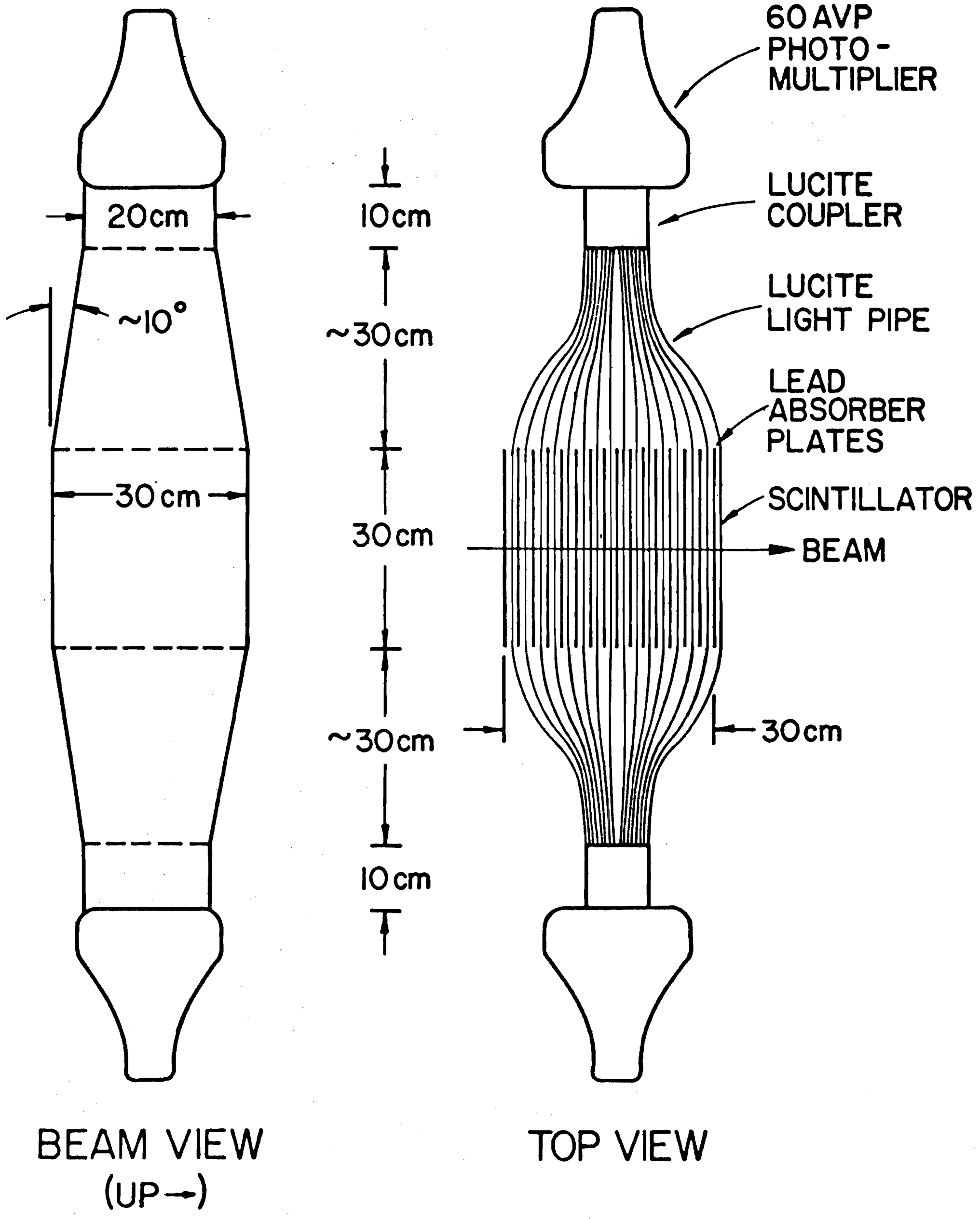
60 AVP PHOTO-MULTIPLIER
LUCITE COUPLER
LUCITE LIGHT PIPE
LEAD ABSORBER PLATES
SCINTILLATOR
BEAM
20cm
~10°
30cm
10cm
~30cm
30cm
~30cm
10cm
30cm
BEAM VIEW
(UP→)
TOP VIEW

Fig. 2

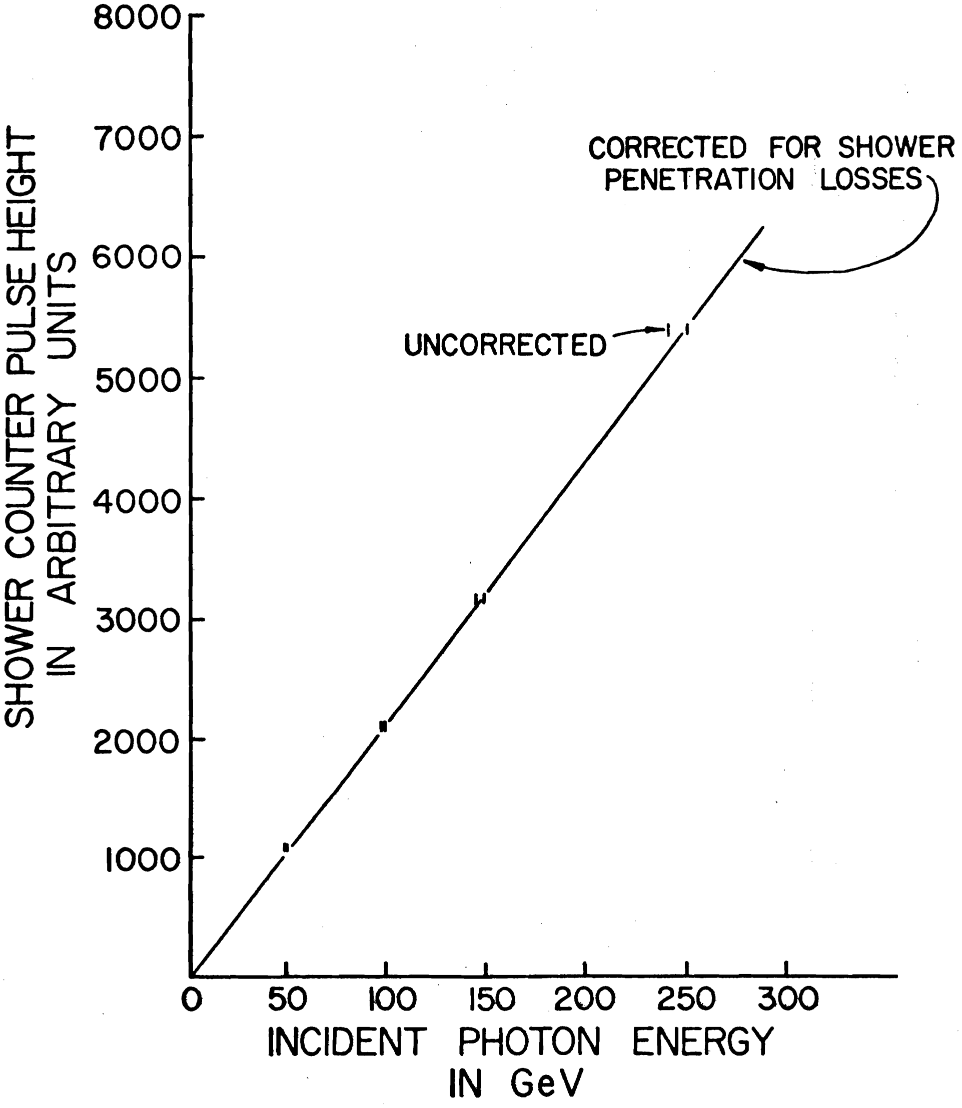
8000
7000
6000
5000
4000
3000
2000
1000
SHOWER COUNTER PULSE HEIGHT
IN ARBITRARY UNITS
0
50
100
150
200
250
300
INCIDENT PHOTON ENERGY
IN GeV
CORRECTED FOR SHOWER
PENETRATION LOSSES
UNCORRECTED

Fig. 3

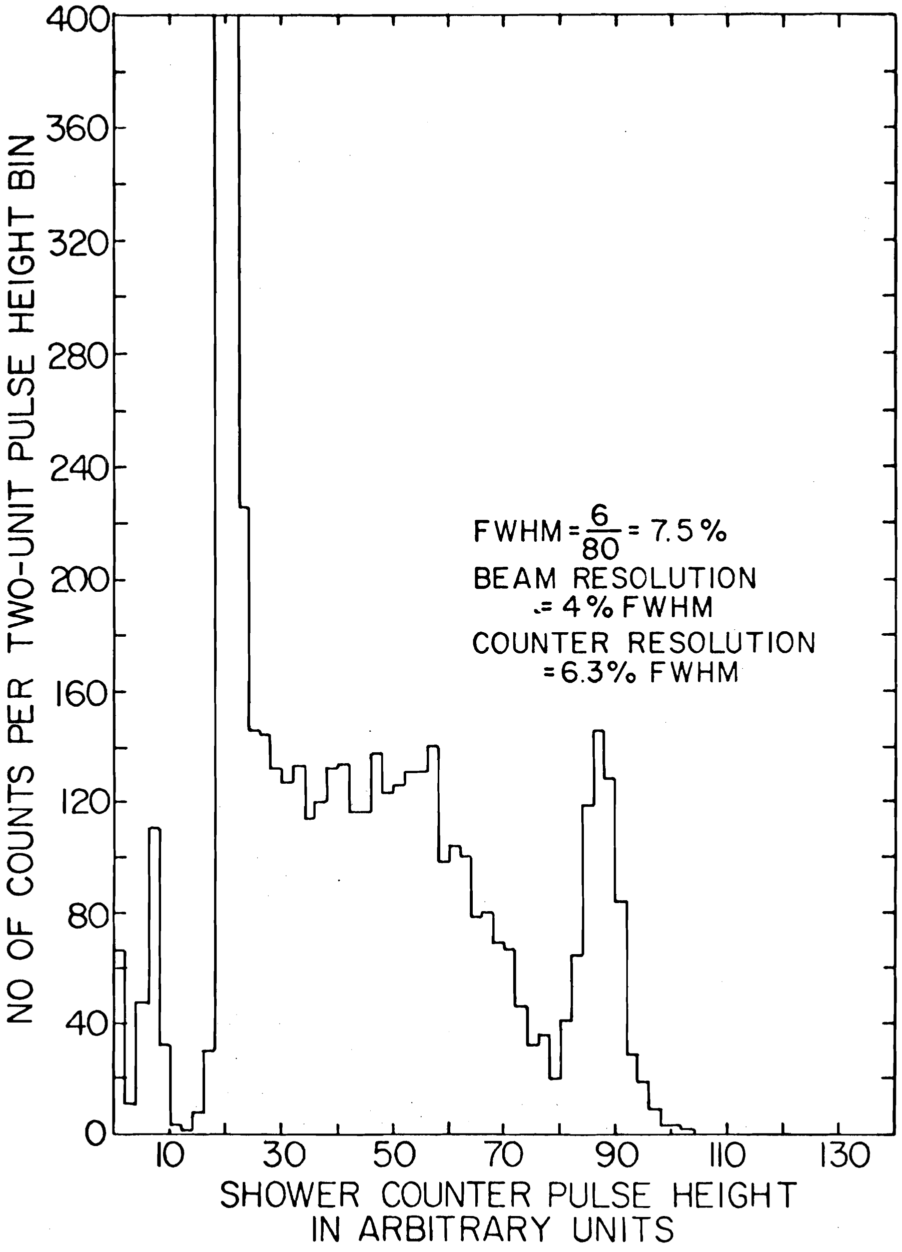
400
360
320
280
240
200
160
120
80
40
0
NO OF COUNTS PER TWO-UNIT PULSE HEIGHT BIN
10
30
50
70
90
110
130
SHOWER COUNTER PULSE HEIGHT
IN ARBITRARY UNITS
FWHM = 6/80 = 7.5%
BEAM RESOLUTION
≐ 4% FWHM
COUNTER RESOLUTION
= 6.3% FWHM

Fig. 4

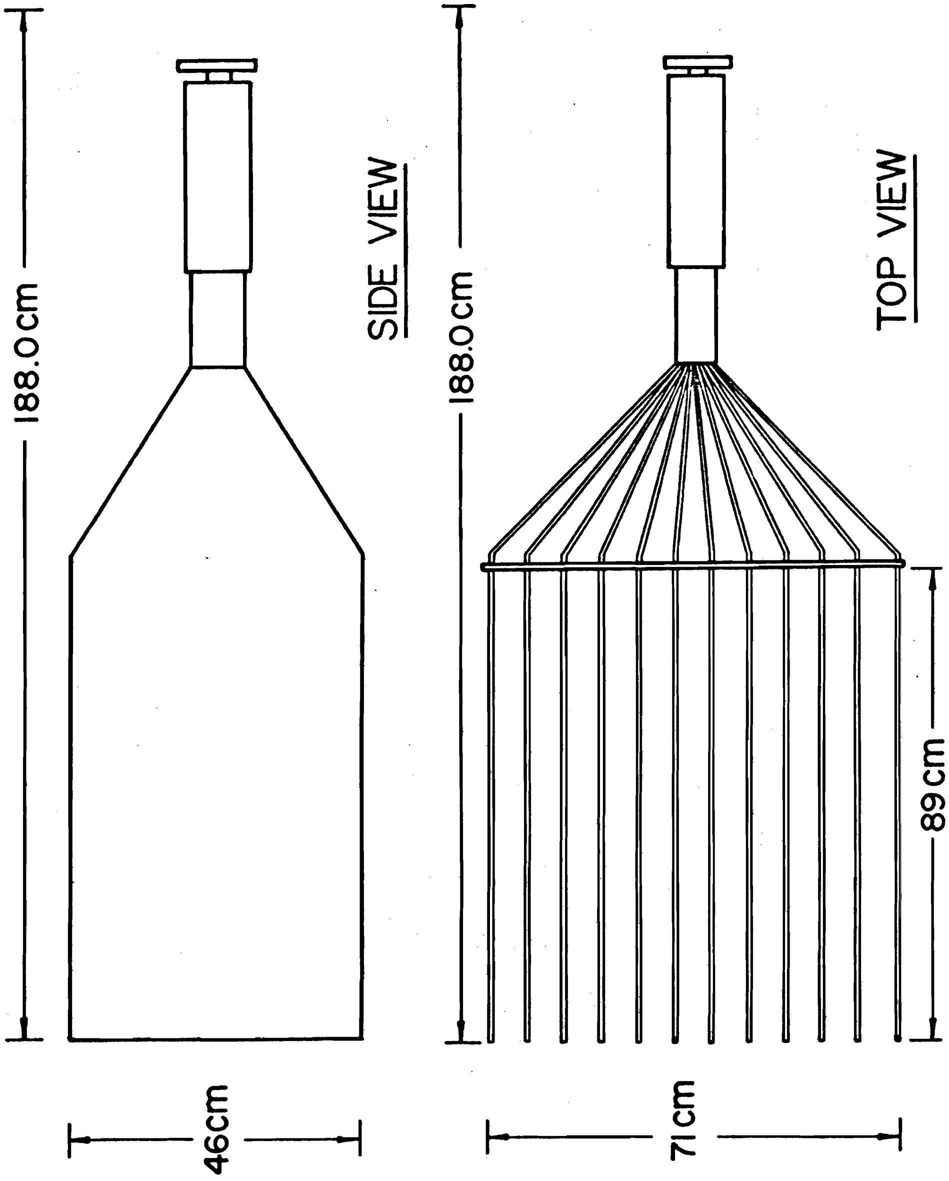

Fig. 5

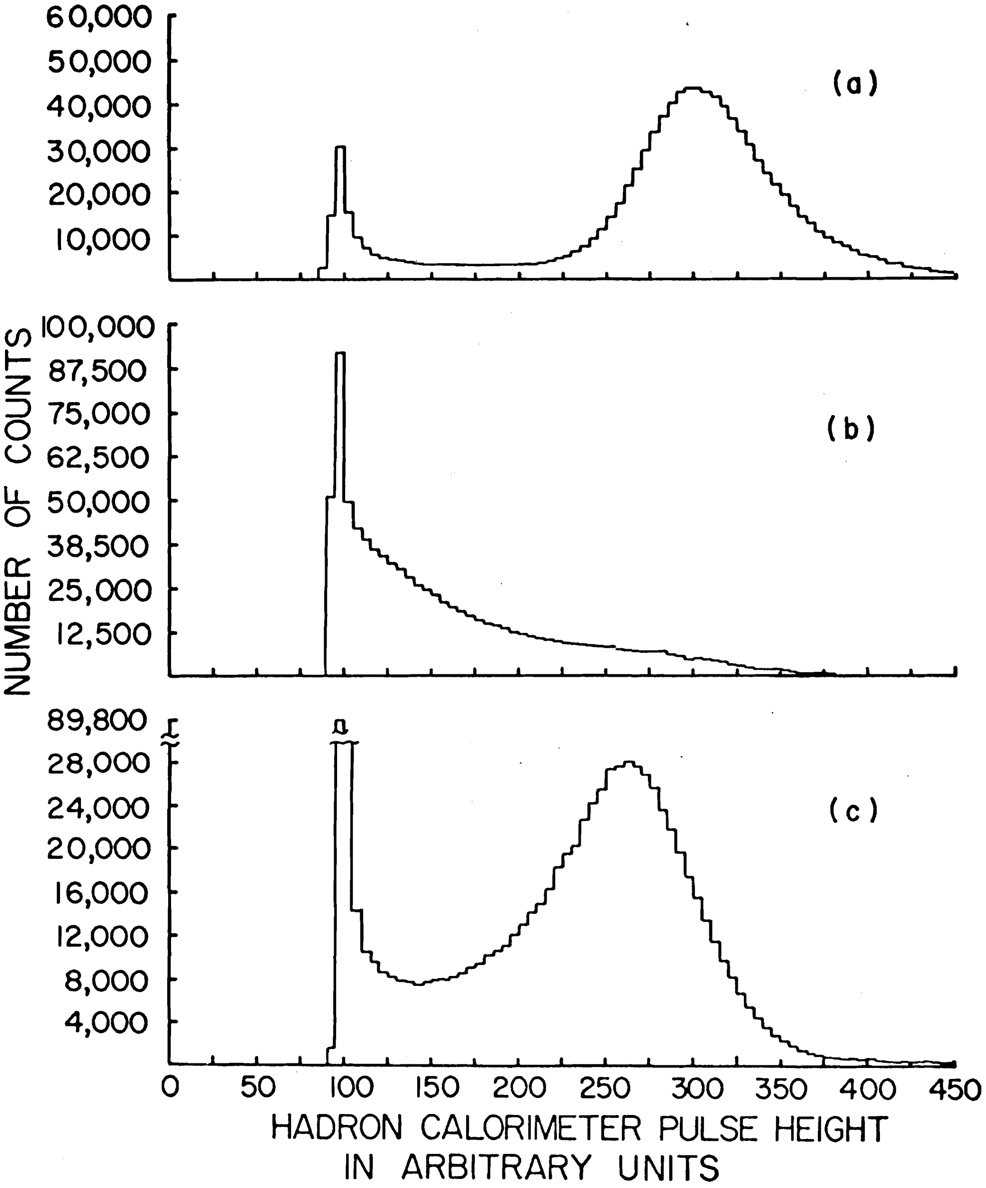
60,000
50,000
40,000
30,000
20,000
10,000
(a)
100,000
87,500
75,000
62,500
50,000
38,500
25,000
12,500
(b)
NUMBER OF COUNTS
89,800
28,000
24,000
20,000
16,000
12,000
8,000
4,000
(c)
0
50
100
150
200
250
300
350
400
450
HADRON CALORIMETER PULSE HEIGHT
IN ARBITRARY UNITS

Fig. 6