FERMILAB-Proposal-0528

PROPOSAL FOR
A DETECTOR DEVELOPMENT STUDY OF ACOUSTIC CALORIMETRY
AT FERMILAB ENERGIES

by

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32 pgs.

*Assuming completion of arrangements for collaboration.

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ABSTRACT

Previous experiments using the BNL proton beam have indicated that the acoustic detection of ionizing events with energies of a few x 10^{13} eV is possible. In order to determine whether that threshold can be decreased to events of a few hundred GeV, we propose to conduct an experiment on the acoustic detection of hadronic cascades. Starting at the level of a few x 10^{15} eV (obtained from a short (less than 100 microsecond) pulse of 10^4 - 10^5 protons of 100 GeV and above in a large tank of water, we will investigate the acoustic radiation pattern and frequency distribution from hadronic cascades. Since technical means appear to be available to greatly increase our sensitivity, we hope to push the threshold down to the point where single neutrino interactions become observable. Should this prove possible, the implementation of very much larger neutrino detectors would then be feasible.

I. INTRODUCTION AND SCIENTIFIC JUSTIFICATION

Recent calculations[1,2] have suggested that the heat deposited by electromagnetic and hadronic showers with energies perhaps as low as 10^{14} eV could produce acoustic pulses in water which would be detectable with state-of-the-art transducers. Searches for acoustic pulses in solids[3,4] have produced signals; however the quantitative interpretation of these results is difficult due to the small size of the targets and the more complicated acoustic behavior of solids.

Current pioneering experiments at Brookhaven[5] have yielded unamplified audible, sonic pulses from total energy depositions in the range of 10^{19} eV, and have mapped out the major characteristics of the acoustic signal.

Figure 1 shows the simple, one period pressure pulse generated in water and detected by standard Navy hydrophones at BNL. This type of signal was observed both from 200 MeV stopping protons from the linac injector and from minimum ionizing 32 GeV protons in small tanks of water (see Fig. 2 and Fig. 3, resp.). The amplitude of the pressure wave varies linearly with the energy deposited (Fig. 4) over 3 orders of magnitude for these large energy depositions. (Neither the 200 MeV linac nor the fast extracted beam could be tuned to lower intensities.) Although it is dangerous to extrapolate these results down several orders of magnitude, the acoustic intensity observed suggests that depositions as low as 10^{13} eV should be detectable above the ambient noise measured at BNL (see Fig. 5).

No attempts were made to use coincidence or phase information, both of which are capable of providing significant improvements in the signal to noise ratio (S/N). Only minimal efforts were expended on shielding the detector in a very noisy environment. Thus, it appears possible that improved experimental techniques may allow the detection of a single cascade in the 10^{11} eV range. If so, acoustic detection may become an important feature of future high-energy neutrino experiments at Fermilab energies. This is due to the inherent simplicity and low cost of the basic transducer (a microphone), the free target material (water), and the long signal attenuation length in the target (1 kM in H_2O for relevant sonic frequencies, compared with 3 m in scintillator for light.) In addition, other inexpensive target materials, e.g., salt, appear promising.

It is clearly essential to check the intensity extrapolation of the nuclear cascade by performing an experiment at Fermilab energies. Connection with the past experiments is easily achieved by interacting many protons in a single short pulse, e.g., 10^6 particles at 400 GeV = 4×10^{17} eV.

Since the entire cascade is produced essentially instantaneously on the time scale of the acoustic signal (for which in sea water c = 1500 m/sec), the frequency characterizing the acoustic radiation is determined by the transit time of a transverse acoustic signal. The general shape of the hadronic cascade resembles that of a horn: narrow near the entrance point, gradually flaring out to maximum width at the end. Thus the transverse transit time varies along the cascade, being shortest at the beginning and greatest at the end. The radiated signal is largely coherent; since the source is essentially linear, and many wavelengths long, the radiation pattern is predominantly a narrow disc in a plane at right angles to the axis of the cascade. The source is not uniform in intensity longitudinally, however, being strongest at the shower maximum, and tapering off in both directions.

BNL Results

The BNL results show that the period of the emitted sound is directly proportional to the diameter of the cylinder of water heated by the beam (see Fig. 6). For a uniform beam over a cylinder of diameter 2d (Fig. 7), the frequency distributions of both the initial compression and the final rarefaction wave show a sharp peak (Fig. 8) at $f = 1/\tau \approx c/2d$, where $c = 1.5$ mm/μs is the velocity of sound in water. In contrast, the Fourier decomposition of the signal from various regions of a fully developed hadronic shower at Fermilab should in principle provide a map of the intensity of energy deposition, revealing the hot core, etc. It may be that intimate details of the hadronic shower can be revealed by ultrasonic imaging - details difficult to ascertain by other methods of calorimetry.

Cascade Detection

We have obtained from A. von Ginneken a computation of the mean shape of nucleonic cascades in water for 400 GeV protons. These data, shown in Figs 9 and 10, help design the detection array. The diameter of the cascade fixes the transverse acoustic transit time across the cascade. This time is the upper limit for the desirable duration of the incident primary proton pulse. Figure 11 shows that the pressure amplitude varies linearly with energy deposition as long as the spill time is short compared to the characteristic dimension at the heat deposition. For longer spills, the energy is not deposited coherently and the output saturates. Thus the Fermilab beam must be comparable to the smallest dimension of the shower that we wish to discern, i.e., ~10μsec if we are to see structures of 1 to 2 cm size.

We will also need a water tank large enough to fully contain a hadronic shower (see Figs, 9 and 10) with walls at least one cascade diameter from the shower. We have considered several methods for constructing large water "swimming pool" calorimeters, suitable for this experiment, including enclosures made from concrete shielding blocks, sheet piling, and wood. All of these are feasible, but our preference has settled on a large cylindrical container already present in the laboratory; The tank formerly served as a liquid oxygen dewar; it is a double-walled cylinder, whose useful internal volume is 10 ft. in diameter and 41.5 ft. long (see Fig. 13). It has four major advantages over the alternative methods; it is here and already constructed; it allows ready pressurization to 160 psi, an important variable we wish to investigate to study the influence of microbubbles on the acoustic signal; it provides perfect optical and electrical shielding; and it is by far the easiest to isolate acoustically from external noise and vibration. It is also the cheapest of the four alternatives.

Summary of Aims

To recapitulate, our study will be the first to investigate high energy hadronic showers with a large sonic detector. It is the natural extension of work which commenced with small sized detectors, in low energy beams at BNL.

If the inexpensive technique of acoustic determination of shower properties like energy direction, and other characteristics does prove feasible in liquids, immediate application can be foreseen in using large masses of water (or other inexpensive material) as particle detectors in third generation (10^{4-5} ton) neutrino experiments.

II. REQUIRED BEAM

The proposed tests require a beam of protons (or other hadrons) of as high an energy as may be conveniently obtained; for definiteness, anything above 100 GeV will be satisfactory. The beam intensity whould be up to 10^5 particles per pulse, but capable of being controlled to levels of one or two. The pulse duration should be controllable from perhaps 100 microseconds down to 10 or even fewer.

Because of the short pulse length required (which follows from the physics of the acoustic emission from the cascade), only the neutrino area seems suitable; short pulses are not available elsewhere.

In the neutrino area, two beams seem to offer the desired particle energy, intensity and duration - the "pinged" bubble chamber beams N3 and N5 (which are branches of the same hadron beam). They are schematically shown in Fig. 13.

The beam requirement are summarized in Table I

Table I

Beam Requirements

Intensity	1 - 10^5 protons/pulse
Energy	High as possible (>100 GeV)
Focus	Symmetrical spot, preferably not over 2 cm diameter Divergence < 10 mr
Time Structure	Need spill length of 10 - 100 μs, preferably hear beginning of flattop.
Monitors	Profile, intensity pulse to pulse readout

Choice of Pulse Length

The required pulse length can be selected from values from about 10 microseconds up to 100 microseconds or even more by using the kicker magnets; there is one in each of the two beams N3 and N5. The purpose of these magnets is to control the total beam exposure of the bubble chambers; they are normally used to divert the beam when enough particles have traversed the chamber. We would control them to produce the desired pulse length. When this period has elapsed, the kicker magnet would move the beam off the collimator slit onto the jaws, where it will be harmlessly absorbed.

Location of Apparatus

We come now to a choice of two possible locations for the experiment, indicated in Fig. 13. One location is at the end of the N3 beam line, behind the 30" bubble chamber. The other is in front of Lab. C, the neutrino detector. This position can be reached by the hadron beam only if the so-called "calibration beam" scheduled for the E-310 neutrino apparatus is completed, so that an adequate beam of protons can be brought to the new calorimeter. The completion of this beam will require the addition of a pair of quadrupoles to allow a proton beam of sufficient energy and intensity to be brought to a focus.

The relative advantages of the two alternative beams are as follows:

1) Installing the apparatus at the end of the N3 beam line will allow the testing of the apparatus with high-energy protons with a minimum of effort; we will be able to investigate the capabilities of the detector for currents from 10^5 particles down to one. This corresponds to 3×10^{16} eV per pulse, down to 3×10^{11}. However, no neutrinos above perhaps 10 GeV reach this area; it is at too large a production angle from the primary beam direction. Thus in this position no tests on neutrino detection could be carried out.

2) Installing the apparatus in front of Lab C, using the calibration beam from N5 would allow all the above measurements, and in addition allow us to search for neutrino-produced events, provided we were successful in our efforts to lower the detection

threshold to a few x 10^{11} eV. It also would obviate having to move the large detector tank from N3 to N5 if the detection of single neutrinos becomes plausible.

Compatibility with Other Experiments in the Neutrino Area

Since the available power supplies are adequate to power either N3 or N5 but not both, clearly operation in either of these lines precludes use of the other. Operation in either line would be compatible with operation of the 15-Ft. bubble chamber, since the latter operates on single-turn beam extraction at the end of the flat-top, while the resonant extraction pulse would presumably come at the beginning. It would also be compatible with use of the N7 proton by-pass for E-369 with the N1 beam and new target station, depending on the setting of a single magnet (the H-magnet) in Nu-hall. Thus, changing the current in this magnet would switch the beam between targets, and thus change experiments rapidly and easily, although both cannot be run at the same time.

The experimental detection of neutrino interactions during the operation of E-310 could possibly be carried out parasitically. The use of the N5 test beam branch will have to be scheduled separately for E-310 and this experiment.

III. DESCRIPTION OF APPARATUS

Detectors

The acoustic detectors will be ceramic piezoelectric (PZT) hydrophones as used in the Brookhaven experiments and in most broad-band underwater acoustics work. Detectors for frequencies up to MHZ are common state-of-the-art devices, with outputs the order of -80 db. resp. 1 volt/microbar. They are coupled to low impedance cables through FET preamps, resulting in systems whose electronic noise is kT limited at approximately 1 nv $Hz^{-1/2}$. Several of these hydrophones will be distributed in the water tank to measure the acoustic signal as a function of position and beam parameters (diameter, current and duration). The signal will be simply related to the direct acoustic pulse for times of a few milliseconds, i.e., long compared with the lowest frequency components of interest. Thereafter the signal will be confused by multipath arrivals. (In later experiments signal processing could be used to deconvolve the signal for longer times in order to improve the s/n ratio in the Fermilab tank. Also in later experiments it may be desirable to servo-support the tank with high compliance pneumatic pistons to isolate it acoustically from ground vibrations. This technique has been applied to smaller systems in aerospace, geophysics, and gravity wave applications.)

Calibration and Testing

A series of tests will be performed to calibrate the response and sensitivity of the detectors and determine the response of the water chamber. The tests will be conducted in part by simulating the time and frequency development of the acoustic pulse. Some useful simulations are 1) a single, thermally pulsed wire, or an ensemble of wires, approximating the expected shower distribution, thermally pulsed, 2) a pulsed laser beam axially along the chamber, 3) tone bursts obtained by using the hydrophones as sources, and 4) RF heating of suspended metallic microspheres to simulate the "hot spot" model of sound generation. Such tests cover a wide enough range of the physical parameters, to permit a first order estimate of the efficiency of detection necessary for the setup of the run.

Monitors

We will require monitors of beam intensity and profile. In addition we expect to install Cerenkov monitors inside the water tank to determine shower locations.

Electronics and Data Processing

Initially, a minimal electronics configuration is envisioned. As shown in Fig. 14, the signals from the hydrophones are amplified, then displayed and recorded by a series of signal processing alternatives.

Our main mode of data recording at the beginning of the experiment will be a group of ADC's and TDC's, supplemented by oscilloscope pictures of the acoustic signals passed through various filters to obtain pulse shape and rough spects. In addition, a sample of the signals will be recorded on a wide-bank instrumental tape recorder. Later in the experiment we expect to obtain on-line FFT (Fast Fourier Transform) spectra for single pulses and a statistical ensemble of pulses. We will probably use a Biomation transient recorder, along with ADC's interfaced into the mini computer for this purpose.

We also expect to use the tank Cerenkov counters to gate the acoustic signal recordings. This will simplify the tasks of relating spatial and angular acoustic distributions to shower location. Among the possible processes are filtering, display on dual beam scopes, and ADC conversion of the filtered or unfiltered signals. The digital time series obtained in this manner will be interfaced via CAMAC into the PDP-11 mini-computer for software FFT processing, and disc or tape storage. The frequency spectrum of the acoustic signal produced in software will provide the opportunity to study coherent representations of the sound pulses, and the phasing of the pulse in the various hydrophones. An understanding of the representation and phasing will allow us to build a model of the pulse production and propagation process. Using this model to properly phase the hydrophone array, the received acoustic signal can be coherently integrated to achieve a potentially much higher ratio of signal to noise.

REFERENCES

[1]B. A. Dolgoshein, Acoustic Signal Detection from $E_o - 10^{16}$ eV Particle Showers, Proc. DUMAND Summer Workshop 1976 (September 6-19, 1976), A. Roberts ed., p. 553; G. A. Askerjan and B. A. Dolgoshein, Acoustic Detection of High Energy Neutrino at Big Depths, Preprint No. 160, Lebedev Physical Institute of the USSR Academy of Sciences, Moscow, 1976.

[2]T. Bowen, Sonic Particle Detection, Proc. DUMAND Summer Workshop 1976 (September 6-19, 1976), A. Roberts ed., p. 523.

[3]B. L. Beron, et al., IEEE Tran. Nucl. Science, Vol. 17, #3 (1970), p. 65.

[4]B. L. Beron and R. Hofstadter, PRL 23, #4 (1969), p. 184.

[5]R. M. White, J. Appl. Phys. 34, 3559 (1963).

[6]Acoustic Detection of Particle Showers, T. Bowen, H. Bradner, W. V. Jones, J. Learned, I. Linscott, A. Parvulescu, B. Pifer, P. Polakos, J. Strait, and L. Sulak, to be submitted to Nuclear Instruments and Methods; see also Studies of the Experiental Feasibility of Acoustic Detection of Particle Showers: Progress Report: Proc. of the 1976 DUMAND Summer Study, A. Roberts, ed., Honolulu, September 6-19, 1976, p. 559 by the same authors.

[7]Fermilab Engineering Note 77-112, January 13, 1977 by W. Nestander: Acoustic Detector Test Tank.

IV. SCHEDULE

Install and test tank	1-2 mos.
Install and test acoustic monitoring equipment	1-3 Mos.
Tuneup with beam	1 week, 1 shift/day
Data taking, protons	1 week, 1 shift/day
Further data, ν's and protons	Request later if justified

V. SUMMARY OF LAB REQUESTS

Tank: Existing Fermilab owned surplus 20K gallon dewar, modified and mounted horizontally.

Beam: ~ 300 GeV protons delivered to tank located directly upstream of Lab. C in the "calibration beam". Alternative location in the N3 line behind 30" BC is temporarily acceptable.

Lab C: Electronics, computer system and portakamp shared on a non-interference basis, including access hole into Lab c.

Other: Small amount of lab electronics.

VI. ROUGH DIRECT COST ESTIMATES

	Fermilab	Outside
Tank moving, modification	$ 15K	———
Hydrophones and preamps	———	$ 5K
Totals	$ 15K	$8.5-15.5K

FIGURE CAPTIONS

Fig. 1: Oscilloscope trace showing single-cycle pressure pulses at beginning and end of the 30 μsec. beam pulse.

Fig. 2: Schematic of the arrangement of apparatus at BNL for detecting stopping 200 MeV protons from injection linac.

Fig. 3: Apparatus for detecting 32 GeV external proton beam.

Fig. 4: Pressure amplitude vs. total energy deposited.

Fig. 5: Ambient acoustic noise measured at BNL.

Fig. 6: Pressure period vs. beam diameter.

Fig. 7: Relation of shower length and near field distance.

Fig. 8: Spectra of acoustic pulses.

Fig. 9: Axial distribution of energy in 400 GeV proton cascade in water (after van Ginneken).

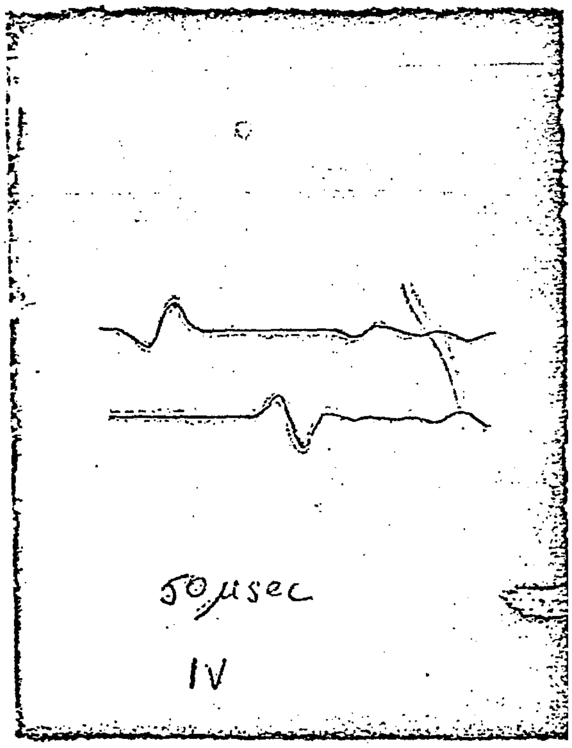
Fig. 10: Same, radial distribution.

Fig. 11: Variation of signal with spill time for 6 cm diameter beam.

Fig. 12: On figure.

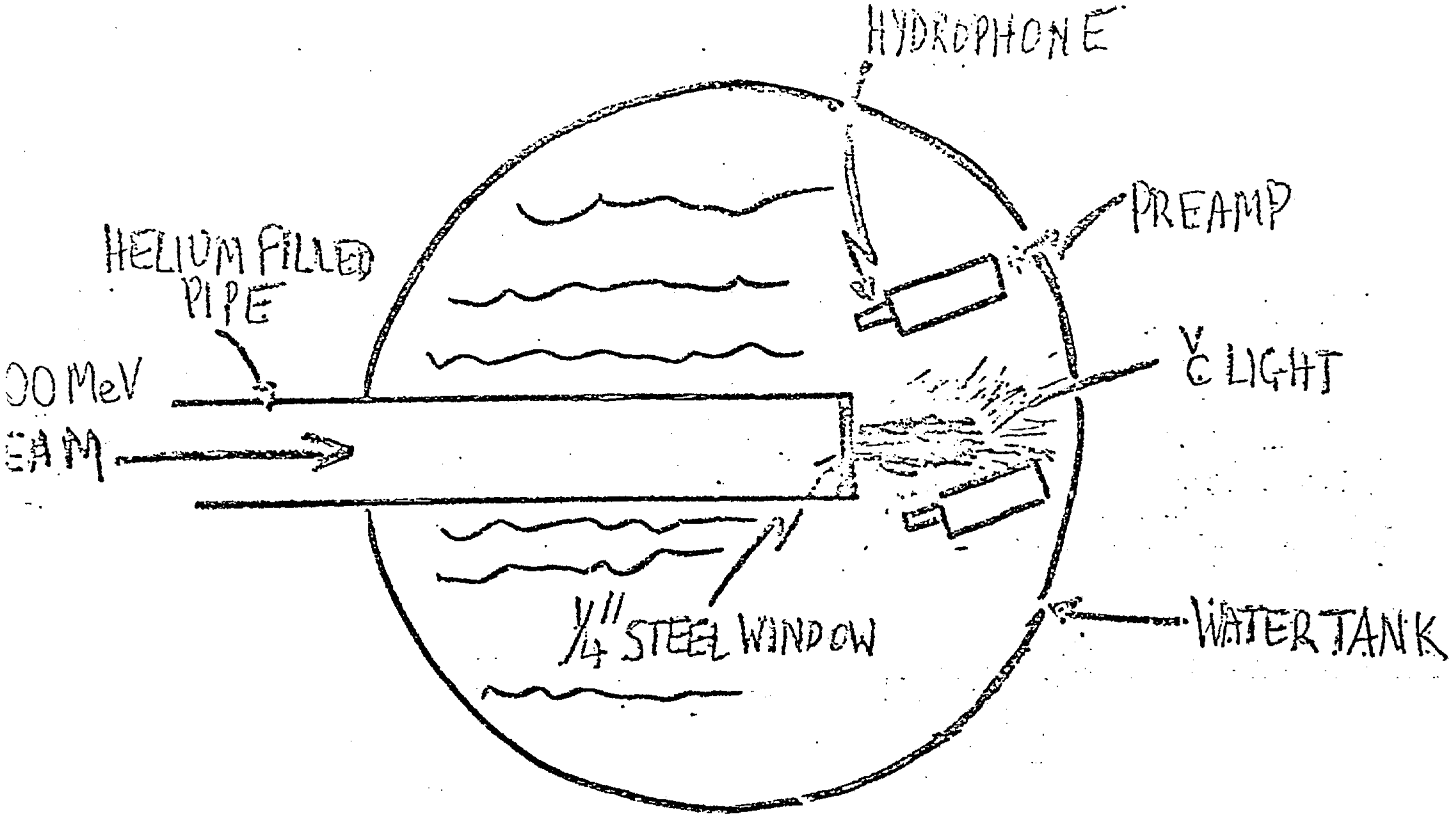
Fig. 13: Possible locations for acoustic calorimeter; Location "A" in front of Lab C, Location "B" behind Lab D.

Fig. 14: Electronics configuration for initial study. Hydrophone signals are amplified and may be displayed on a dual beam scope in filtered or unfiltered form. In addition the signals may be recorded on a wide-band instrumentation tape recorder, or on a PDP-11.

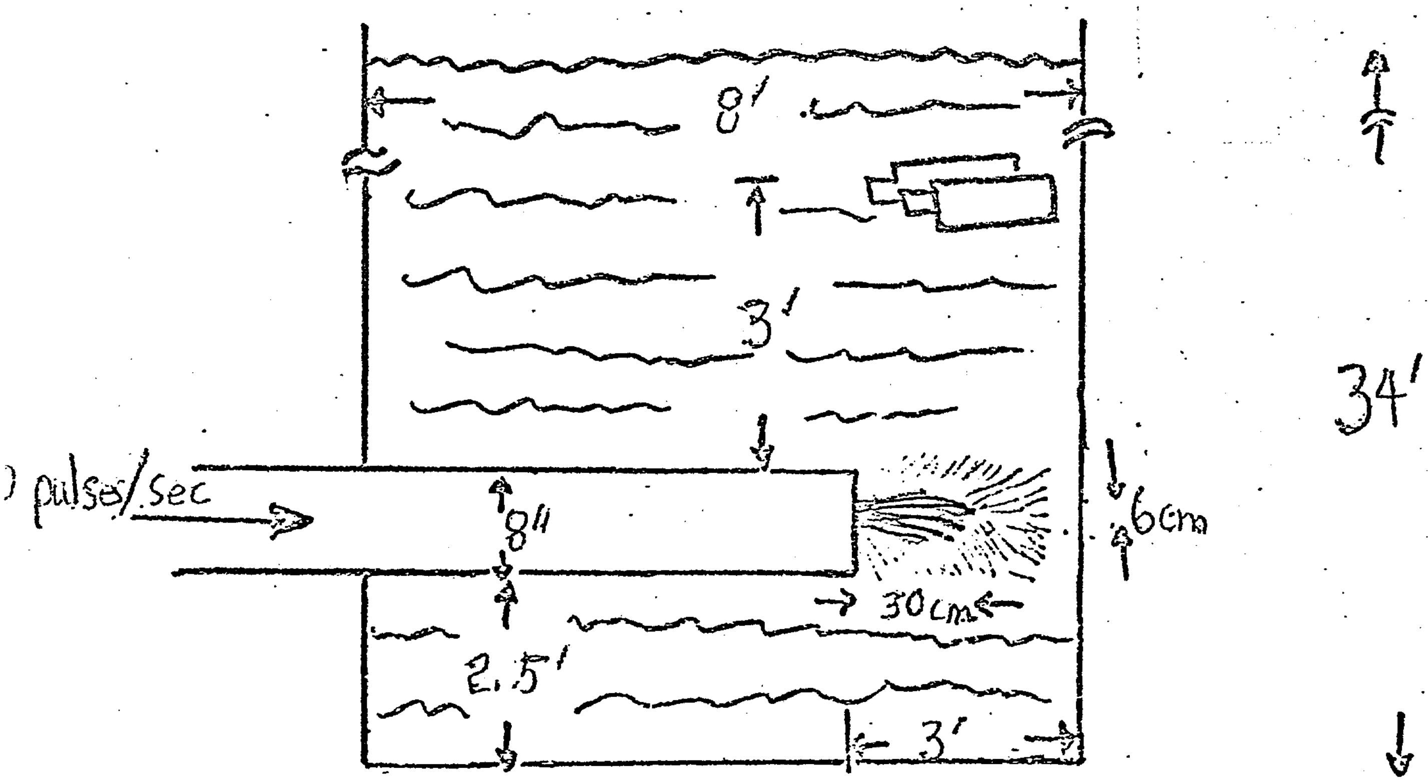


4ma, 30μsec-SPILL

Fig. 1

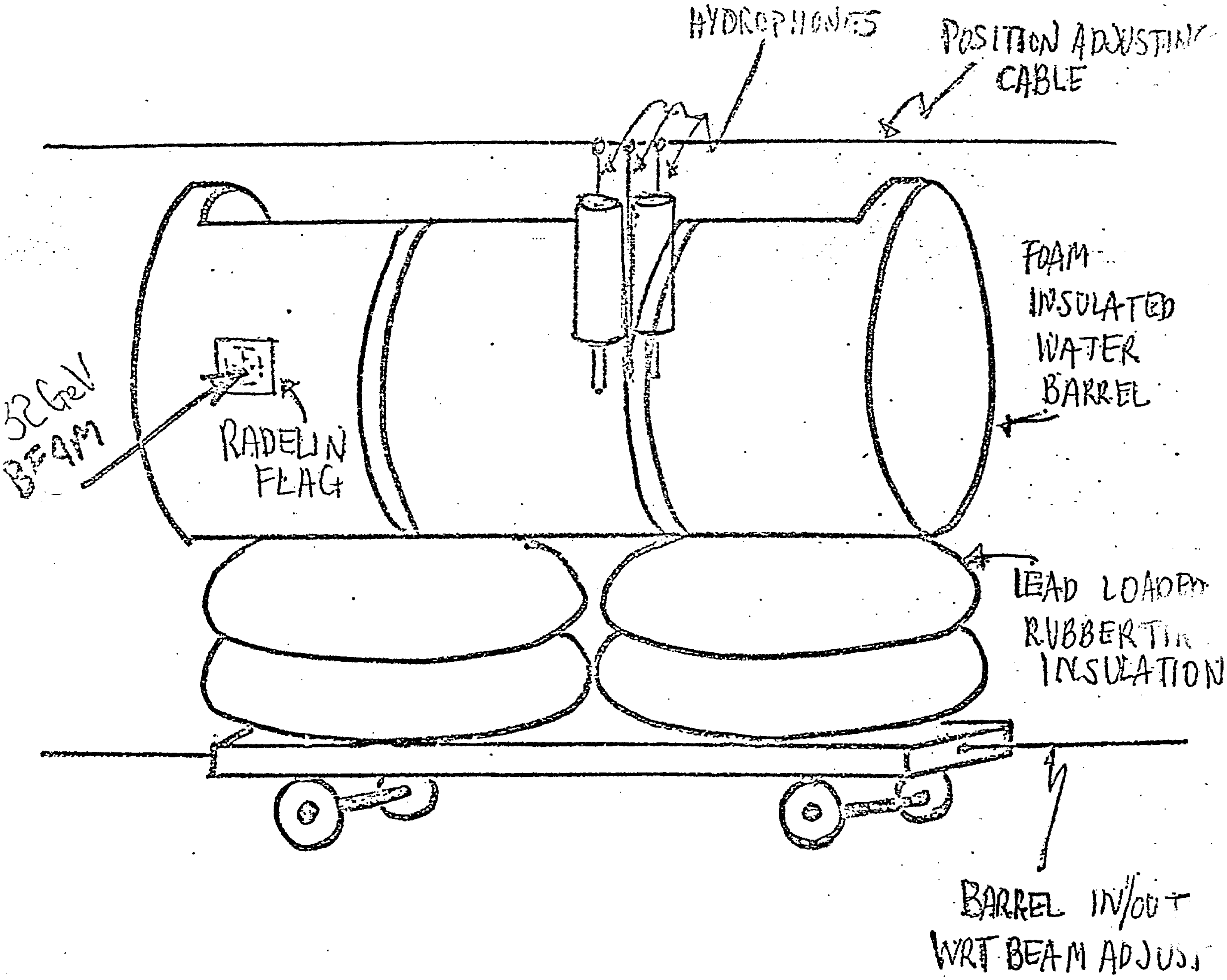


TOP VIEW



SIDE VIEW

Fig. 2



FRONT VIEW

Fig. 3

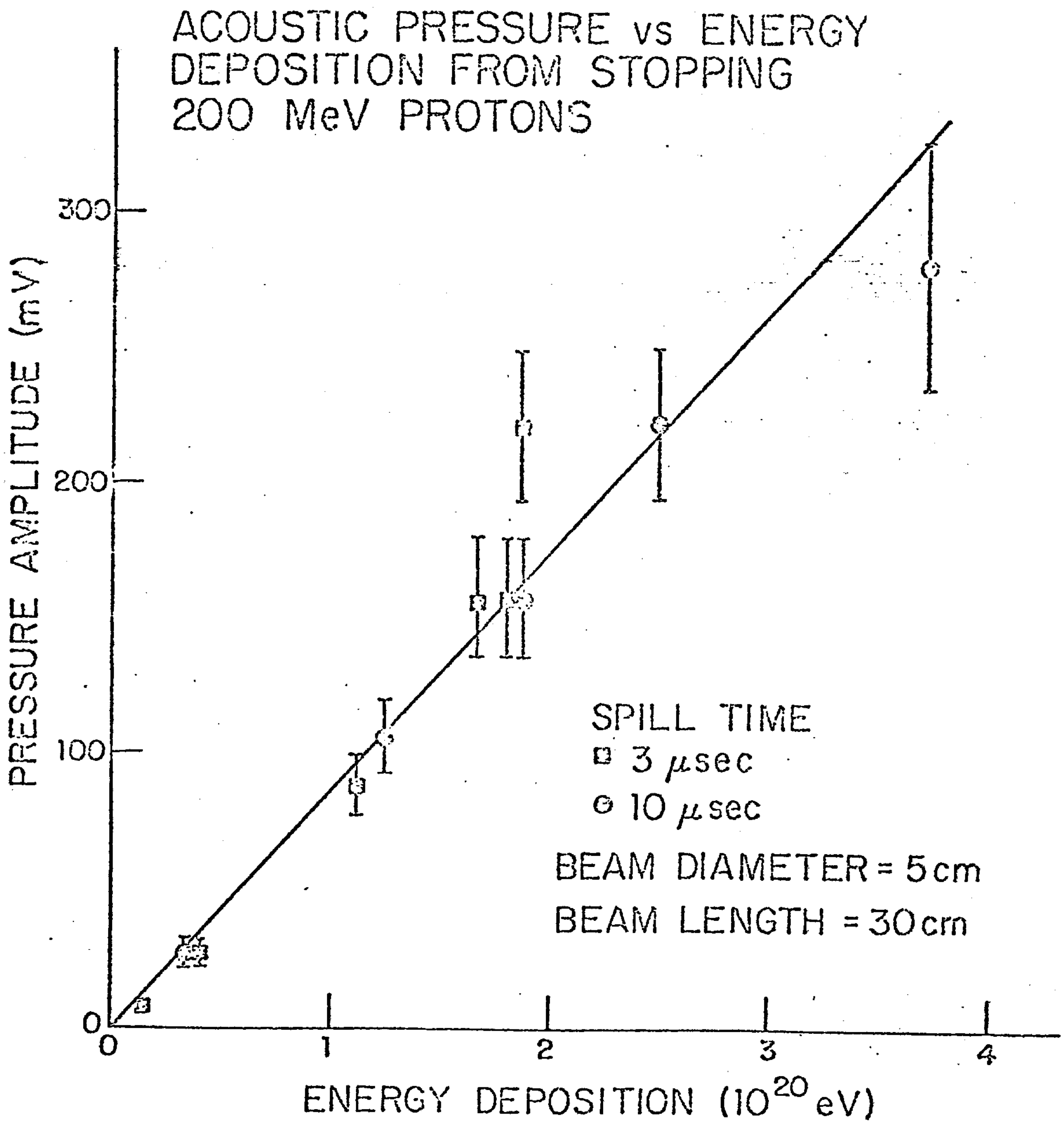

ACOUSTIC PRESSURE vs ENERGY DEPOSITION FROM STOPPING 200 MeV PROTONS
PRESSURE AMPLITUDE (mV)
300
200
100
0
0
1
2
3
4
ENERGY DEPOSITION (10^{20} eV)
SPILL TIME
3 μsec
10 μsec
BEAM DIAMETER = 5cm
BEAM LENGTH = 30cm

Fig. 4

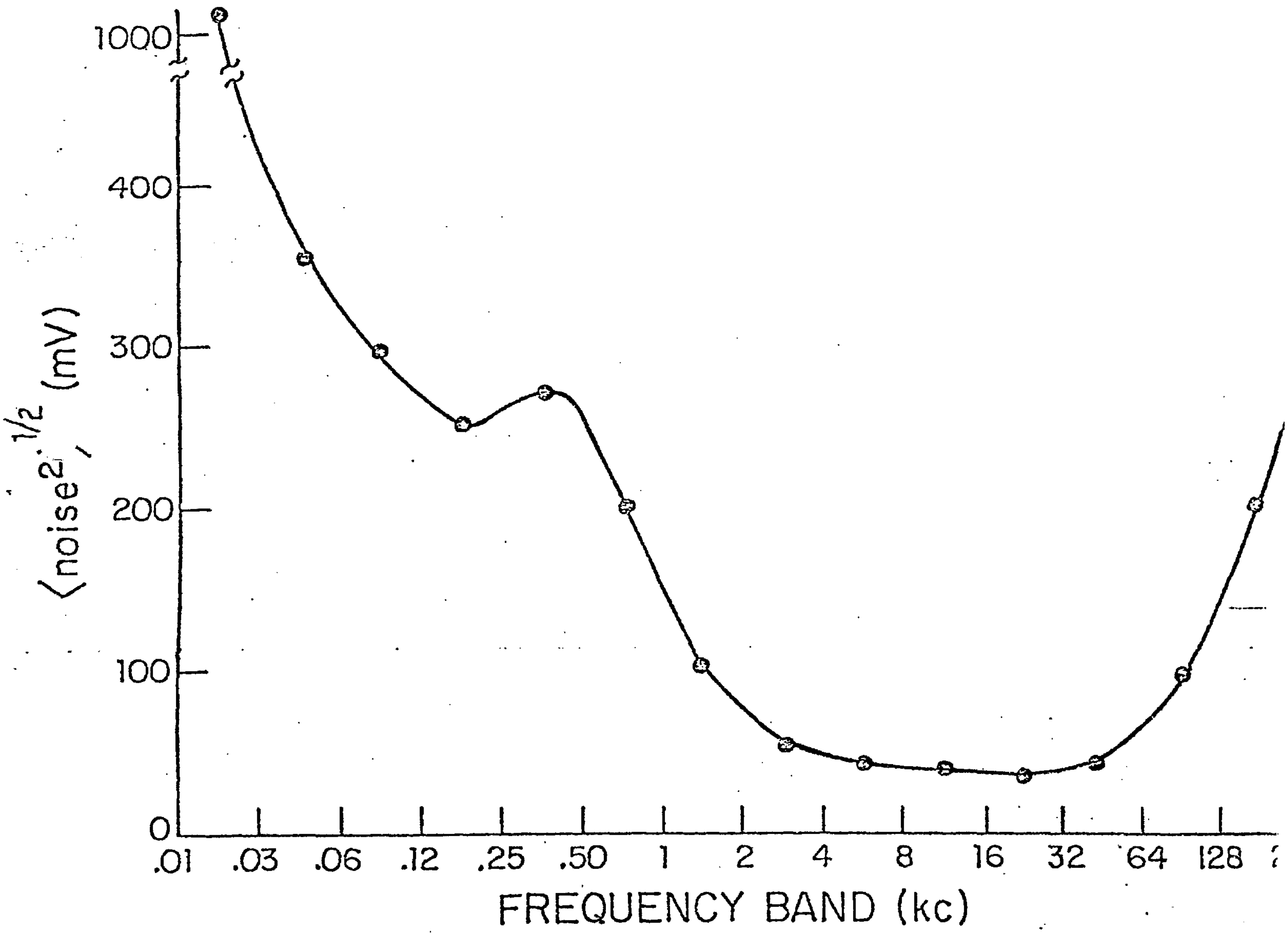

1000
400
300
200
100
0
⟨noise²⟩^½ (mV)
.01
.03
.06
.12
.25
.50
1
2
4
8
16
32
64
128
FREQUENCY BAND (kc)

Fig. 5

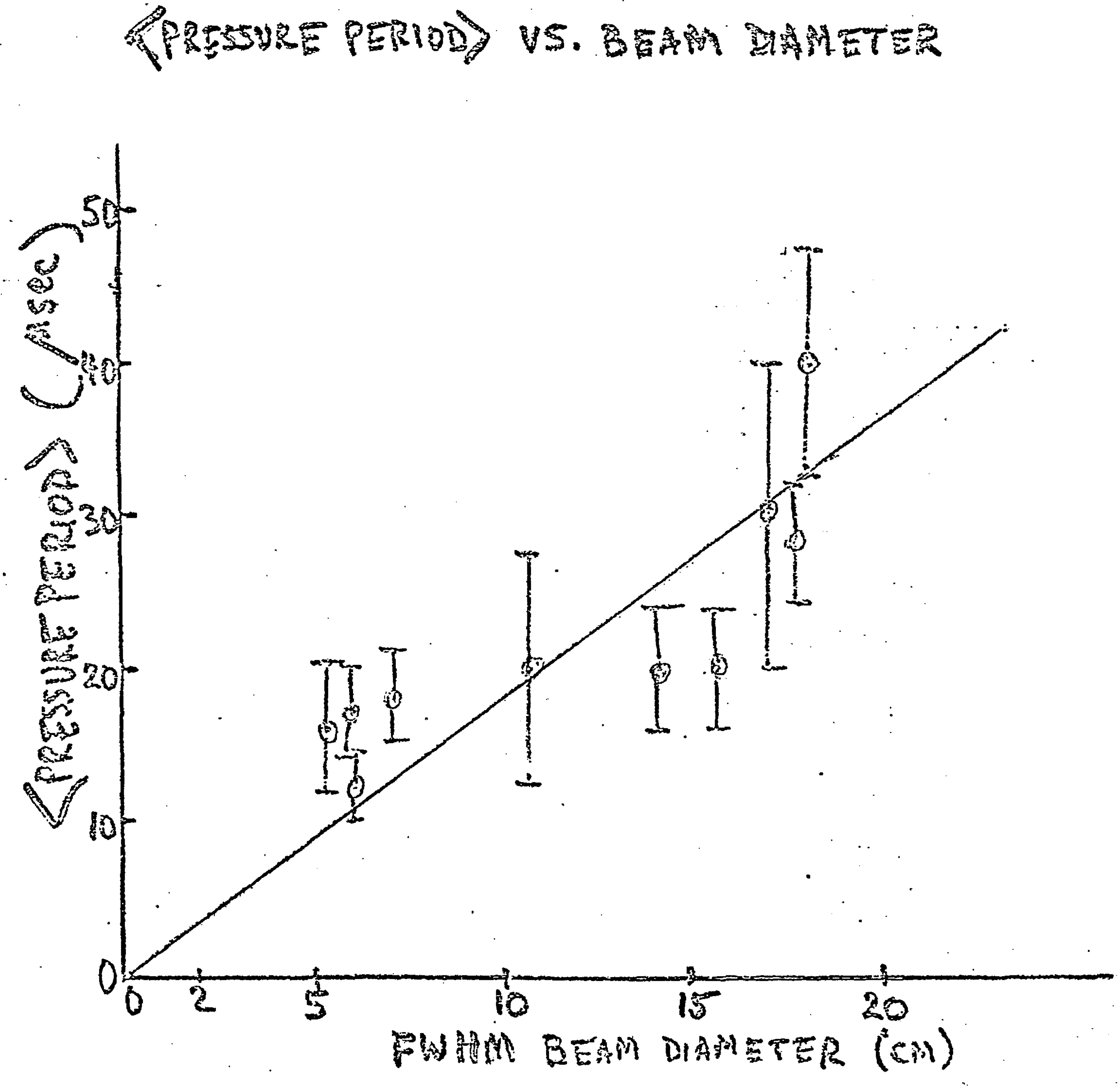

<PRESSURE PERIOD> VS. BEAM DIAMETER
<PRESSURE PERIOD> (μsec)
50
40
30
20
10
0
0
2
5
10
15
20
FWHM BEAM DIAMETER (cm)

Fig. 6

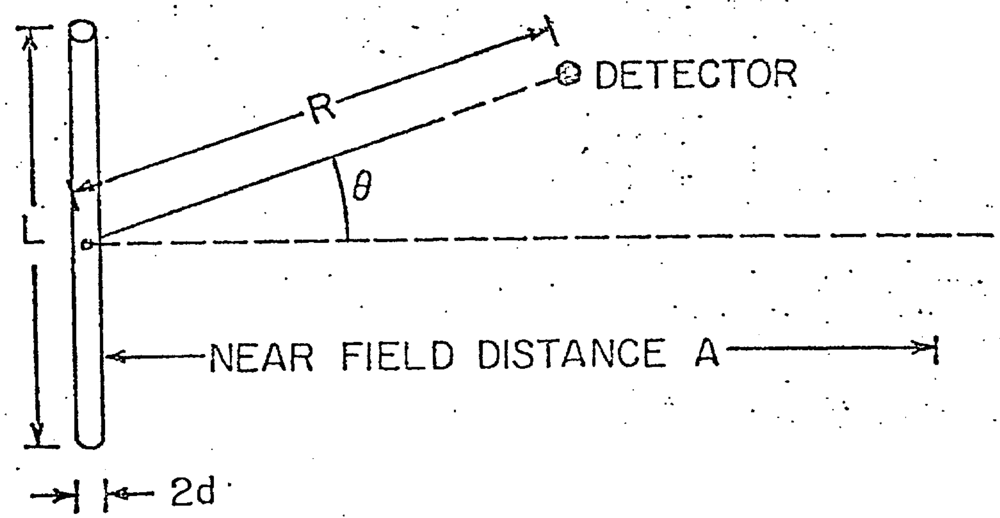


Fig. 7

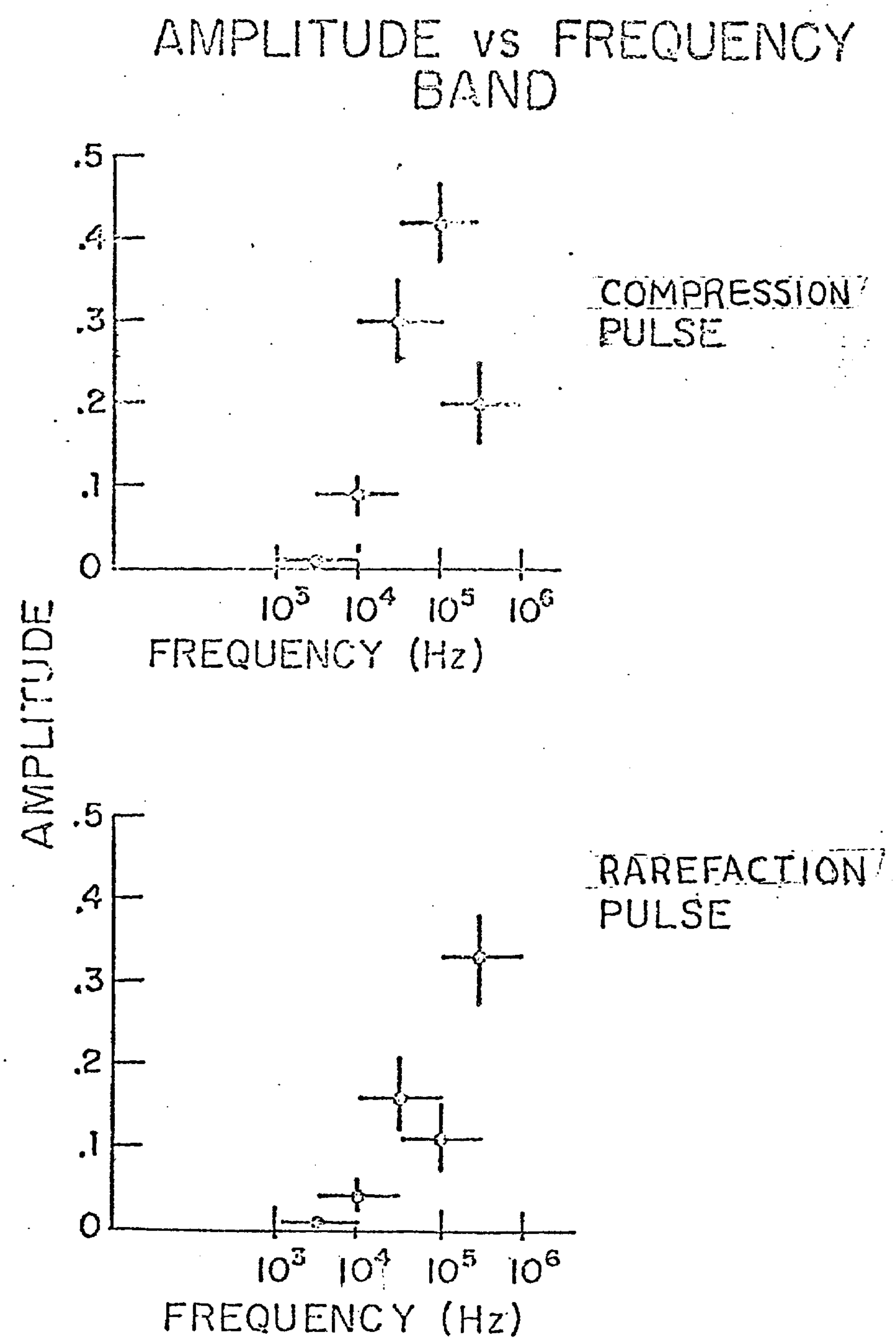

AMPLITUDE vs FREQUENCY
BAND
COMPRESSION
PULSE
RAREFACTION
PULSE
AMPLITUDE
.5
.4
.3
.2
.1
0
10³ 10⁴ 10⁵ 10⁶
FREQUENCY (Hz)

Fig. 8

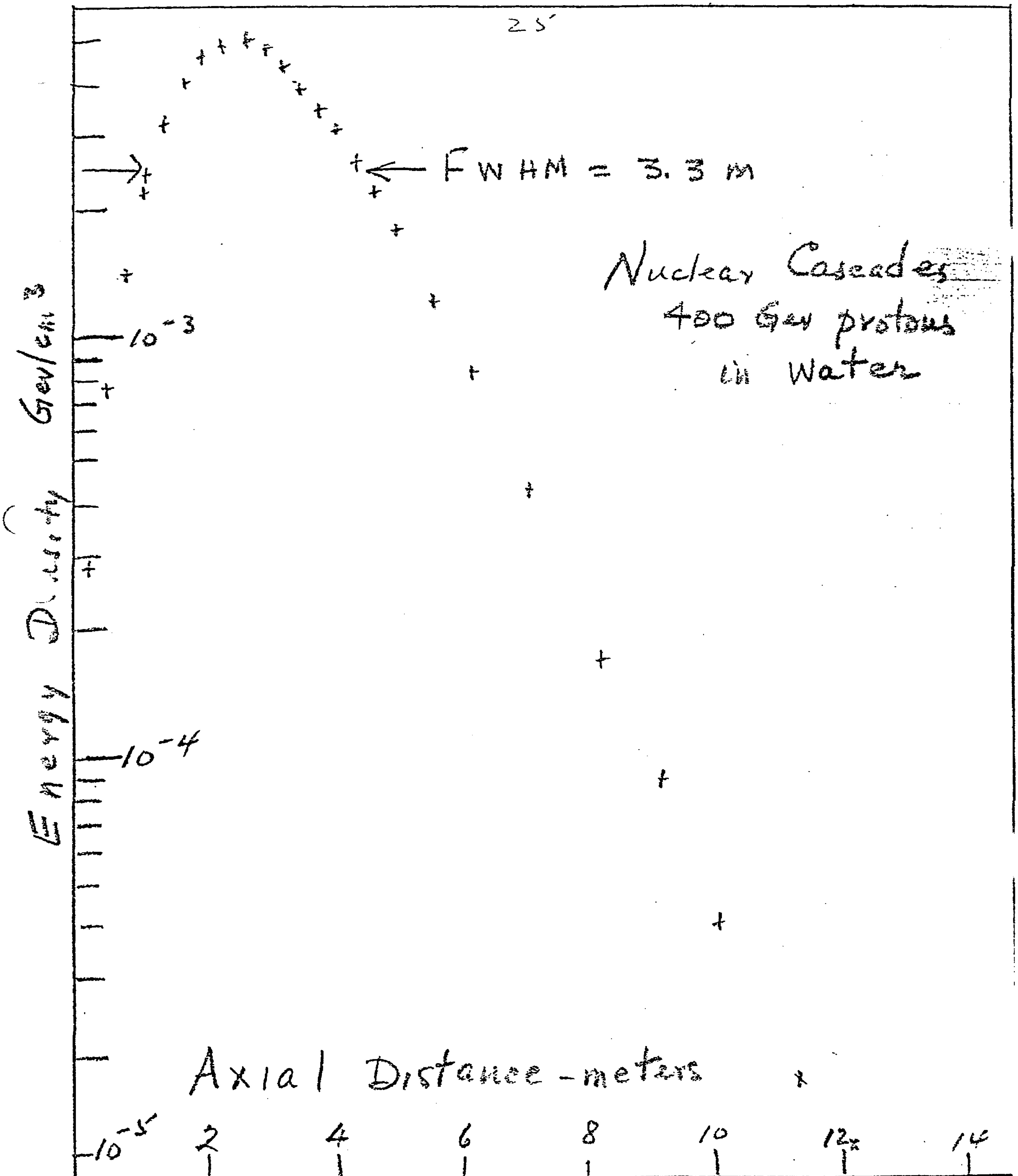

25
FWHM = 3.3 m
Nuclear Cascades
400 Gev protons
in Water
Energy Density Gev/cm3
10-3
10-4
10-5
Axial Distance-meters
2
4
6
8
10
12
14

Fig. 9

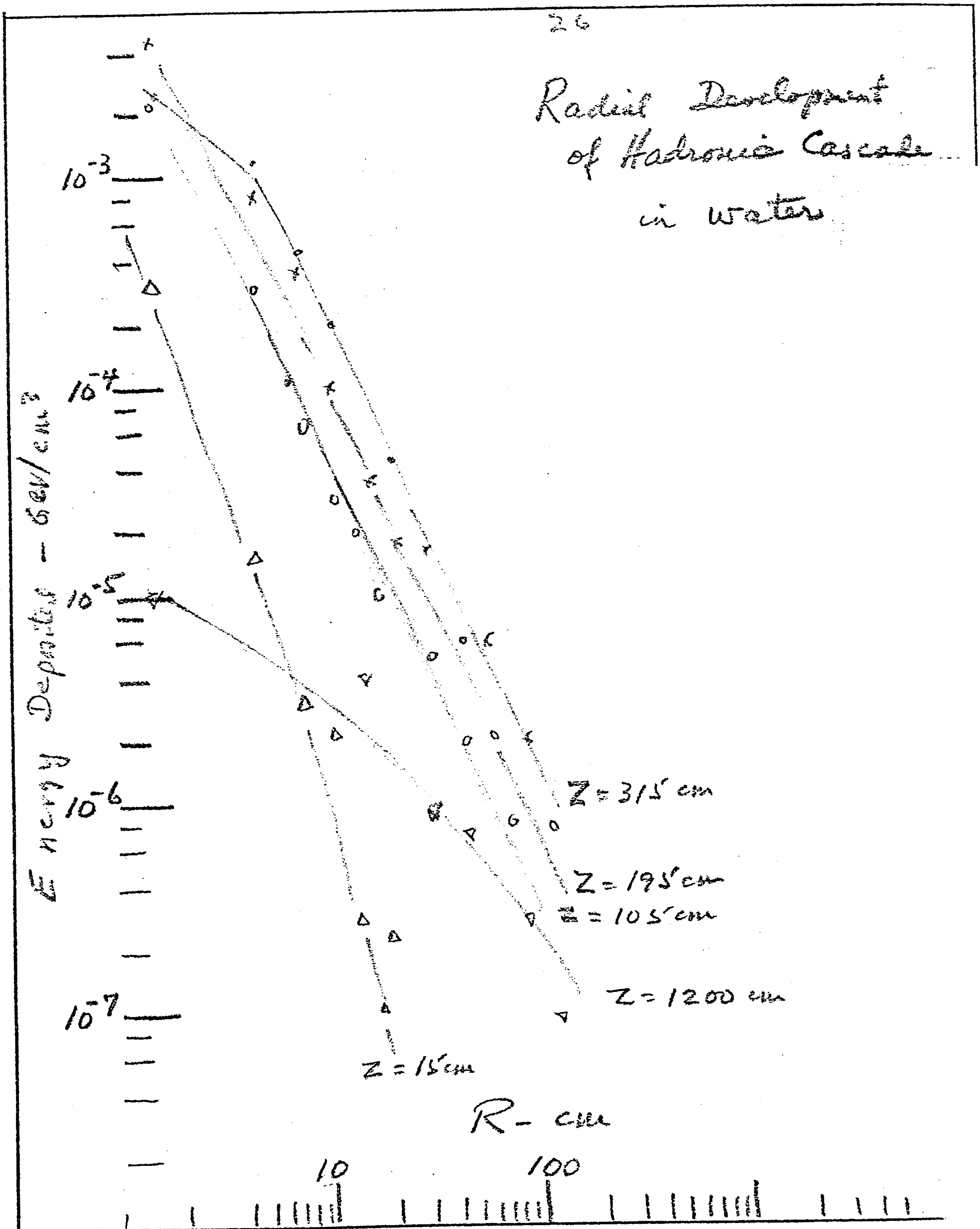

Radial Development
of Hadronic Cascade
in water
Energy Deposited - GeV/cm³
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
Z = 315 cm
Z = 195 cm
Z = 105 cm
Z = 1200 cm
Z = 15 cm
R - cm
10
100

Fig 10

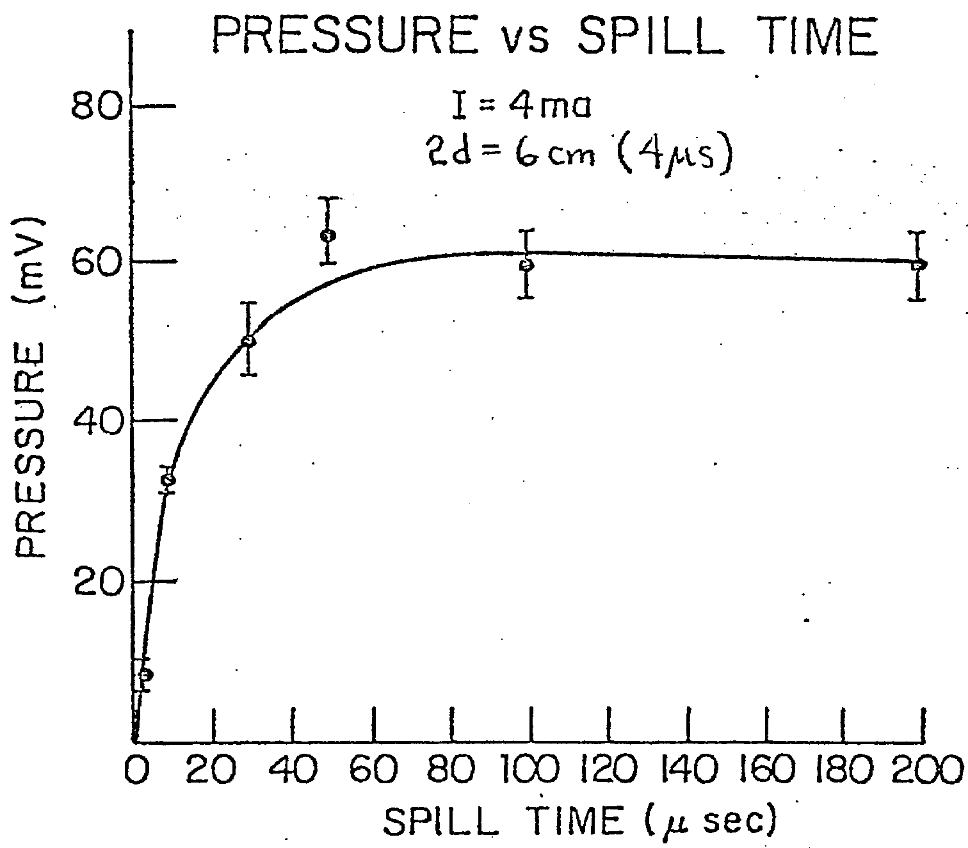

PRESSURE vs SPILL TIME
I = 4ma
2d = 6cm (4μs)
PRESSURE (mV)
80
60
40
20
0
20
40
60
80
100
120
140
160
180
200
SPILL TIME (μ sec)

Fig. 9I

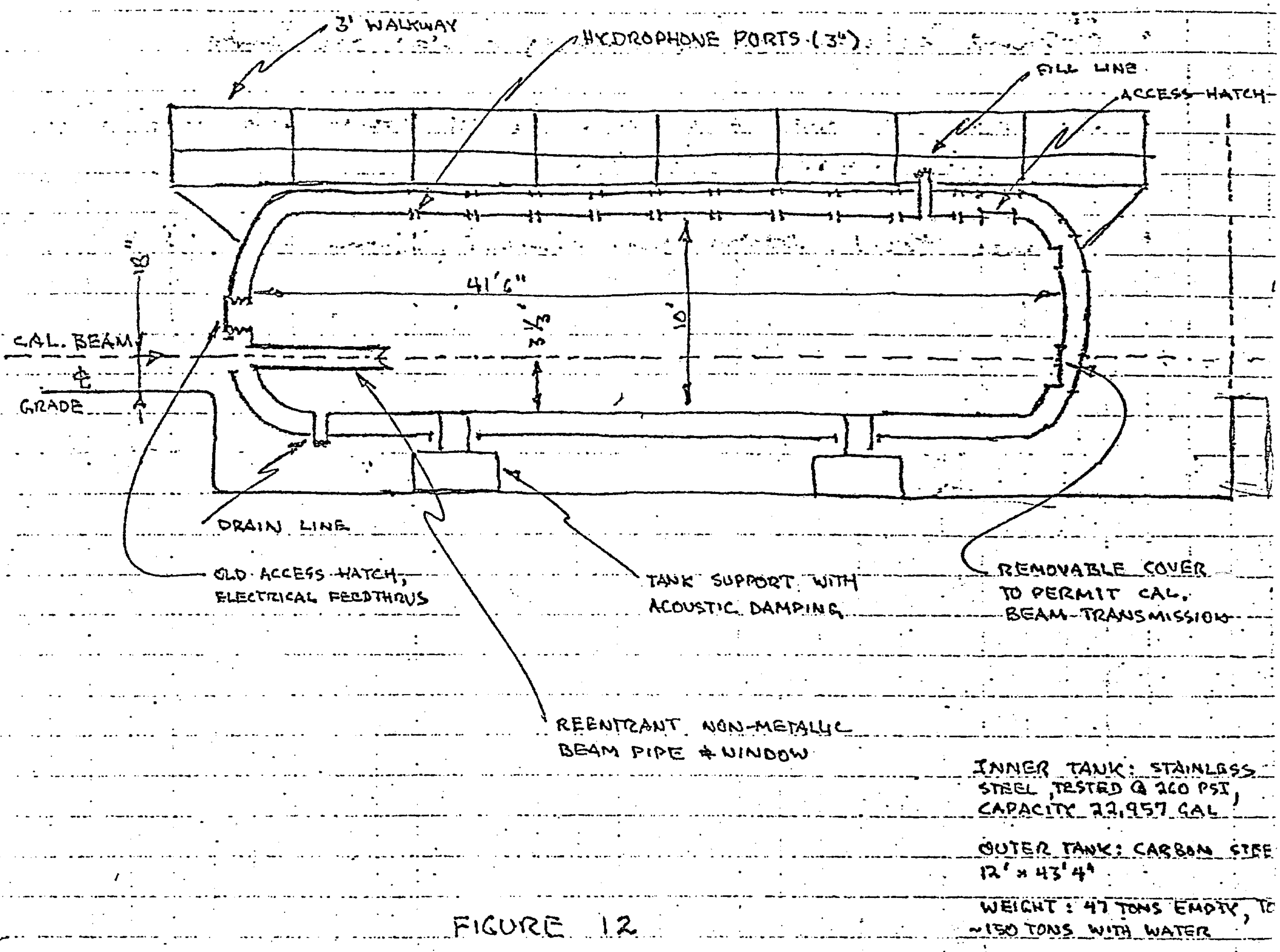
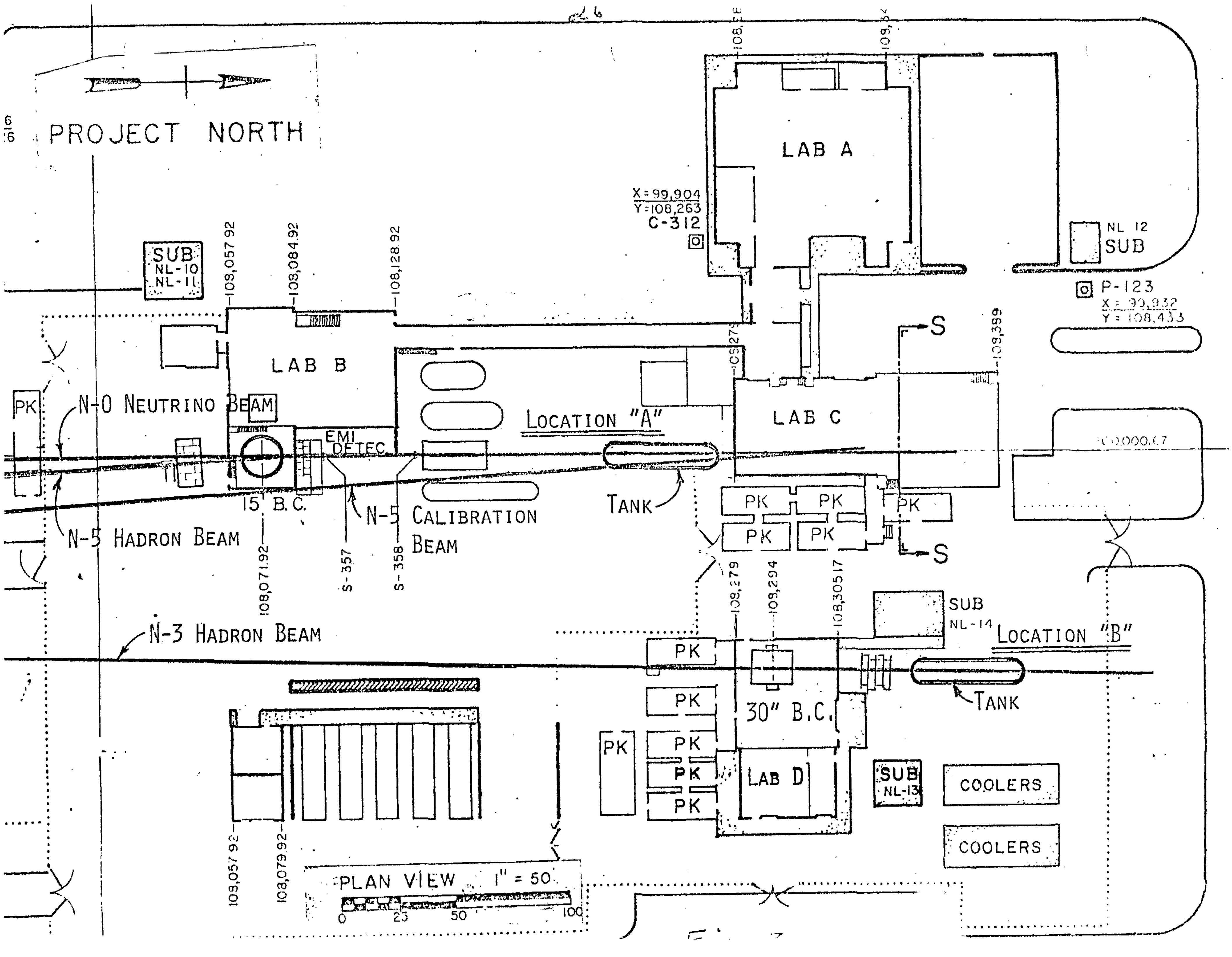


FIGURE 12

CROSS SECTIONAL SKETCH
TANK INSTALLATION
23K GAL SURPLUS DEWAR


PROJECT NORTH
LAB A
X=99,904
Y=108,263
C-312
NL 12
SUB
P-123
SUB
NL-10
NL-11
108,057 92
108,084.92
108,128.92
LAB B
N-0 NEUTRINO BEAM
LOCATION "A"
LAB C
EMI
DETEC
15' B.C.
TANK
N-5 CALIBRATION
BEAM
N-5 HADRON BEAM
108,071.92
S-357
S-358
PK
S
108,279
108,294
108,305.17
SUB
NL-14
LOCATION "B"
N-3 HADRON BEAM
30" B.C.
LAB D
COOLERS
108,057 92
108,079.92
PLAN VIEW 1" = 50
0
25
50
100

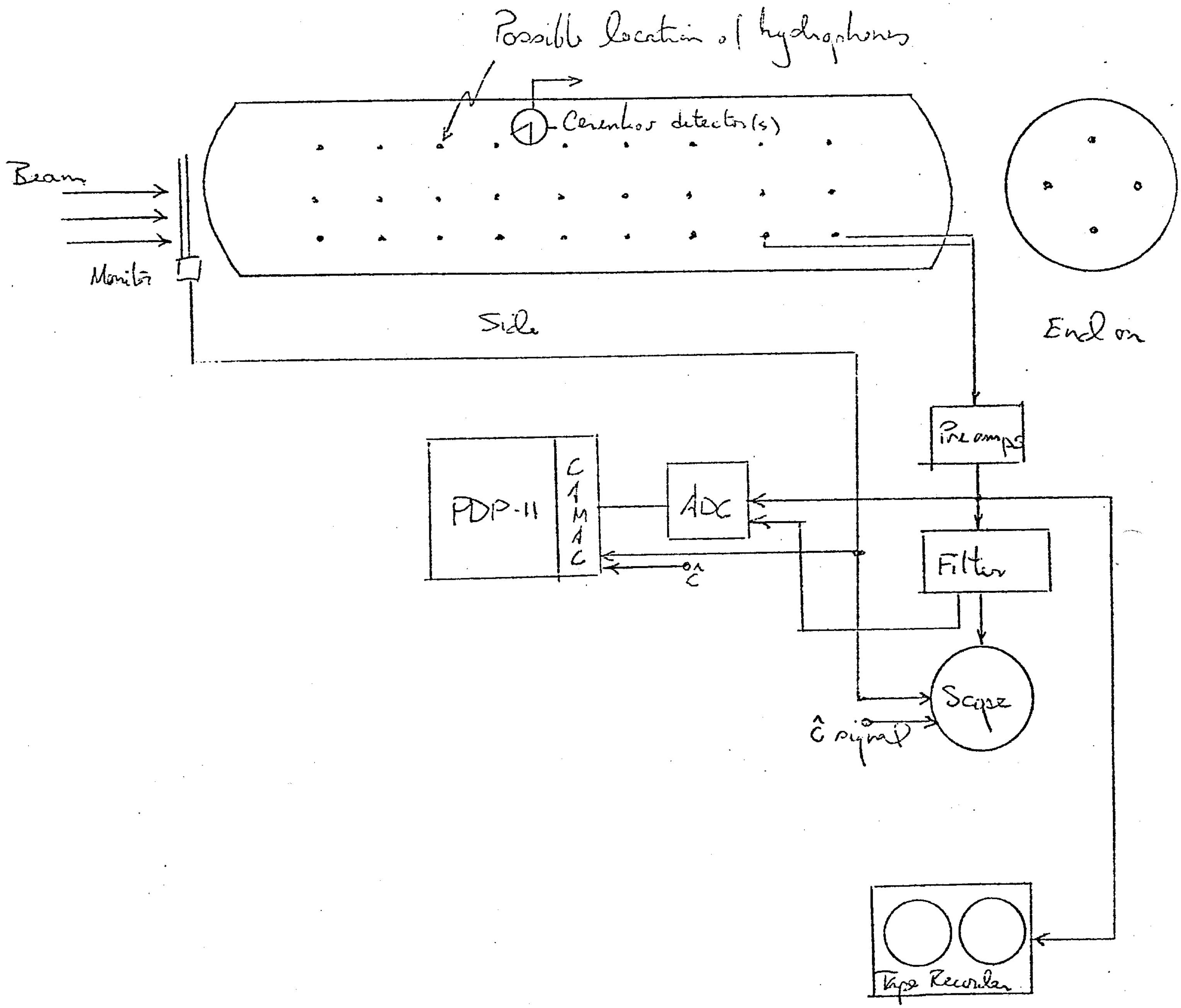

Possible location of hydrophones
Cerenkov detector(s)
Beam
Monitor
Side
End on
Preamps
PDP-11
CAMAC
ADC
Filter
Scope
Ĉ signal
Tape Recorder

Fig. 14