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DEVELOPMENT AND PERFORMANCE
OF
A HIGH PRESSURE HYDROGEN TIME PROJECTION CHAMBER

Thomas J. Chapin, Rodney L. Cool, Konstantin Goulianos,
Jerome P. Silverman, Gregory R. Snow, Harry Sticker,
and Sebastian N. White

The Rockefeller University, New York, NY 10021 USA

and

Yue-Hua Chou

Institute of High Energy Physics
Beijing, The People's Republic of China

ABSTRACT

We describe a high pressure hydrogen gas time projection chamber (TPC) which is presently operating at Fermilab both as target and as recoil detector in an experiment investigating the diffraction dissociation of photons on hydrogen, $\gamma p \rightarrow Xp$. The TPC, which consists of two cylindrical drift regions each 45 cm in diameter and 75 cm long, measures the polar angle and the energy loss dE/dx of the recoil protons. Typically, at 15 atm of H_2 with 2 kV/cm drift field and 7 kV on the 35 μ sense wires, the drift velocity is about 0.5 cm/ μ sec and the spatial resolution $\pm 200\mu$.

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I. INTRODUCTION

We have built a high pressure hydrogen gas time projection chamber (TPC) which is currently operating at Fermilab as part of a recoil spectrometer in an experiment investigating the diffraction dissociation of photons on hydrogen, $\gamma p \rightarrow Xp$. The chamber acts both as target and as track detector of recoil protons. It consists of two cylindrical drift regions arranged in tandem, each 45 cm in diameter and 75 cm long. The beam is directed along the axis of the cylinder. Ionization electrons from protons recoiling in a direction transverse to the beam drift along axial electric field lines to the end plates of the chamber where they are detected by a set of concentric octagonal sense wires. The chamber measures the polar angle θ and the energy loss dE/dx of the recoil protons. The energy of the protons is determined by stopping them in plastic scintillation counters located inside the high pressure vessel. Typically, at 15 atm of hydrogen with 2 kV/cm drift field and 7 kV on the 35 μ diameter sense wires, the drift velocity is 0.5 cm/ μ sec and the spatial resolution $\pm 300\mu$. In what follows, we discuss briefly the experiment for which the chamber was designed and we present details on the construction and performance of the recoil spectrometer with particular emphasis on the TPC.

II. THE EXPERIMENT - TPC Design Considerations

The experiment for which the hydrogen TPC was designed, Fermilab E-612, measures the inclusive cross section $d^2\sigma/dtdM_x^2$ for $\gamma p \rightarrow Xp$ in the region $0.02 < |t| < 0.1 \text{ (GeV/c)}^2$ and $M_x^2/s \lesssim 0.1$. It uses the tagged photon beam ($20 \lesssim p_0 \lesssim 170 \text{ GeV/c}$) and employs a recoil detector (TREAD - The Recoil Energy and Angle Detector) that measures the energy and the polar angle of recoil protons in the region $10 < T < 50 \text{ MeV}$ and $45^\circ < \theta < 90^\circ$. The variables t and M_x^2 are then determined from the measured quantities p_0 , T and θ

$$t = -2M_p T \quad (1)$$

$$M_x^2 = 2p_0 \sqrt{|t|} (\cos \theta - \sqrt{|t|} / 2M_p) \quad (2)$$

where M_p is the mass of the proton.

A schematic drawing of the experimental arrangement is shown in Figure 1. Recoil protons are detected in TREAD. Downstream of TREAD two 1/8 inch thick scintillation counters measure the charged multiplicity while a lead-glass array (not yet commissioned) will measure the neutral energy of the dissociation products.

The goal of the experiment is to study the known resonances, to search for new resonance structures in the inclusive photodissociation cross section, and to measure the low t "missing mass" continuum. Figure 2 shows the mass spectrum expected from 50 GeV photons. Good mass resolution is essential to the study of the resonances. Typical resolutions

are shown in Figure 3. A resolution of $\Delta M_x^2/M_x^2 = \pm 0.03$ maybe obtained in the region $0.05 < M_x^2/s < 0.1$ with $\Delta p_o/p_o = 0.02$, $\Delta t = 0.002 \text{ (GeV/c)}^2$ and $\Delta\theta = 0.005$. For $M_x^2/s < 0.05$, better angular resolution would be needed. The required resolution in t is achieved by stopping the protons in scintillation counters and using the pulse height to measure their energy. The resolution in θ is limited by the multiple Coulomb scattering in the target-detector combination. A liquid hydrogen target would be inadequate. For example, the multiple scattering of 25 MeV protons ($|t| = 0.05$) in 1 cm of liquid hydrogen results in $\Delta\theta = \pm 0.010$. Good angular resolution for low energy recoils requires the use of a gas target. The material along the path of the protons inside the recoil detector must also be kept small. Event-rate considerations dictate the use of a high pressure target and a large solid angle detector. The TPC that we have built is a target-detector combination that satisfies these requirements.

III. TREAD (The Recoil Energy and Angle Detector) - An Overview

The recoil detector consists of two identical endcap assemblies mounted on a 26" I.D. $\times$ 84" long stainless steel tube. A schematic drawing is shown in Figure 4. The vessel may be pressurized up to 20 atm with hydrogen. The beam enters through a 2" dia. $\times$ 0.030" thick hemispherical beryllium window. Recoil protons from interactions of the beam with the hydrogen are stopped in 1 1/8" thick scintillation counters placed 9" away from the axis inside the high pressure vessel. The energy of the protons is determined from the counter pulse heights. Particles penetrating these

counters register on anti-counters. The photon dissociation products exit through an 8" dia. $\times$ 0.080" thick aluminum window (not shown in the figure).

The ionization electrons generated along the path of the recoil proton drift along axial electric field lines towards a ground plate where they are detected by a set of concentric octagonal sense wires. The sense wires and associated electronics record the time and measure the amount of the ionization as it arrives. Time differences between sense wires are then translated into polar angles and pulse heights into dE/dx . From dE/dx and T (recoil energy measured by pulse-height counters) the mass of the recoil may be calculated.

The drift velocity of electrons in hydrogen is a function of E/N , the ratio of the electric field to the gas density. Angle measurements of the required accuracy demand tolerances on the electric field, temperature and pressure on the order of 0.1%. The temperature is maintained constant by an automatically controlled heating jacket surrounding the vessel. A pressure transducer¹⁾ controlled with preset limits activating input and exhaust solenoid valves keeps the pressure within tolerances. In practice, allowing the gas to leak at a slow constant rate maintains the pressure within 0.01 psi of the low preset threshold. Finally, the electric field is kept uniform²⁾ by two "cages" of field-shaping metal rings. The outer cage, located outside the scintillation counters, consists of 48 rings made of 1/8" copper wire connected by 100 M Ω metal film resistors³⁾. These rings are insulated from the wall of the vessel by a 1/2" thick polyethylene tube. The thickness of the wire was chosen to prevent corona discharge.

The inner cage is located inside the scintillation counters. Since it is in the uniform field formed by the outer rings, corona discharge is not a problem and therefore thin wire could be used for its construction. This cage consists of 96 rings of 0.002" diameter Cu-Be wire connected to a bleeder chain made of $2 \times 22 \text{ M}\Omega$ 1 Watt carbon resistors per stage. The space between the high voltage plate and the ground sense wire plate is completely enclosed by these rings, a condition that must be satisfied to achieve uniform electric field throughout the entire drift chamber.

A cross section of the recoil spectrometer is shown in Figure 5. Each of the eight sense wire octagons is segmented into two halves in such a way that a count in a pulse-height counter doublet, covering $1/8$ of the azimuthal angle, may be correlated with a track pointing to the doublet. This information is incorporated in the trigger in order to reduce background.

The sense wires are located in the centers of $1/4$ " square grooves machined on the face of a $1/2$ " thick aluminum plate. Figure 6 shows the position of a sense wire in a groove and the resulting electric field lines under normal operating conditions. With this arrangement, a track segment of length approximately equal to the width of the groove is focused onto each sense wire.

As seen in Figure 4, a two-layer solenoidal magnet coil surrounds the vessel. This was designed to produce a 1 kG magnetic field to confine Compton electrons of energy ≤ 1 MeV within the beam region and away from the sense wires. A thermal insulation layer separates the vessel heating jacket from the water-cooled magnet coils.

Figure 7 is a photograph of a partially completed endcap assembly ready to be inserted into the TREAD vessel. The outer cage field-shaping rings are clearly visible. The crane being used is mounted on the TREAD frame and was designed for this purpose. Figure 8 is a photograph of a completed endcap assembly viewed from the high voltage side of the TPC.

IV. TREAD - Apparatus Details

In this section, we discuss details of the high pressure vessel, the beam windows, the scintillation counters, the TPC, the sense wire electronics, and the radioactive source assemblies used for calibration and monitoring of the TPC.

A. High Pressure Vessel.

The vessel was designed to hold 20 atm of hydrogen. Its 84" long by 26" I.D. cylindrical shell was cold-rolled from 1/2" thick Type 304 stainless steel. The 36" diameter by 2 1/2" thick endcaps, which had to be magnetic to provide a return path from the magnetic field, were made of Type A515 steel. Both the 304 steel and the A515 are immune to hydrogen embrittlement under our normal operating conditions⁴⁾ (pressure, temperature, stress).

All gas, electrical and lightpipe connections to the inside of the vessel are made through the endcaps. Viton O-rings are used for all seals. The scintillation counters and drift chambers are supported mechanically from the endcaps. Structural supports are made of G10 or aluminum.

B. Beam Windows.

TREAD employs two beam windows, a 2" dia. $\times$ 0.030" entrance window made of Type S-65 beryllium alloy and an 8" dia. $\times$ 0.080" exit window made of Alcad 2024-T3 aluminum. Both windows are of the same design (see Figure 9) and were machined from single blocks of material in order to minimize mounting stresses and facilitate stress calculations.

The beryllium window is mounted on an 11" dia. A515 steel flange 2 1/2" thick at its center which is itself mounted on the front endcap (see Figure 4). This arrangement minimizes the amount of strain transmitted from the endcap to the window when the vessel is pressurized. The aluminum window is mounted directly on the rear endcap.

C. Scintillation Counters.

Each endcap assembly has 16 pulse-height counters (PH) and an equal number of anti-counters (A). The PH counters are 30" long $\times$ 1 1/8" thick and have a trapezoidal cross-section with large sides of 3" and 3 3/8" (see Figure 5). The A counters are 30.5" long $\times$ 3.5" wide $\times$ 1/4" thick. All counters are made of NE-110 plastic scintillator.

The scintillator slabs are coupled to RCA-8575 phototubes through UVT lucite lightpipes. The latter penetrate the endcaps so that the phototubes are outside the pressure vessel. Gas sealing is achieved with special stainless steel clamps which compress O-rings around the lightpipes and onto the endcap faces on the outside of the vessel.

An encapsulated 1/2" dia. $\times$ 1/4" long α -source of ^{241}Am adjacent to a NaI crystal⁵⁾ is glued at the far end of each PH counter facing the phototube. These sources are used as constant output light pulsers for monitoring the gain stability of the counters.

D. Time Projection Chamber.

The TPC was described in some detail in section III. Each of its two identical halves consists of a high voltage plate, a sense wire plate and two "cages" of field-shaping rings (see Figures 4,5,7 and 8). An electric potential of up to -200 kV between the high voltage and sense wire plates may be provided by a power supply through an RG-220 cable. The cable enters the vessel through one of the endcaps and is connected to the high voltage plate of the corresponding half of the TPC. The electrical connection to the plate of the other half of the TPC is accomplished through a spring attached to one of the plates. These plates are made of aluminum and are 1/4" thick with rounded edges. A 6" dia. hole at the center of each plate, covered with thin household aluminum foil for electrical continuity (see Figure 4), allows the beam and the photon dissociation products to go through.

The sense wires we use are stainless steel or nichrome of 35 μ diameter. Gold-plated tungsten wires of the same diameter did not work as well. They usually broke down before reaching a useful operating voltage, presumably due to poor surface characteristics. The sense wires are mounted in the grooves of the sense wire plates (see Figure 6) on posts located at the corners of the octagons. The posts are glass tubes of 1/8" O.D. that go through the sense wire plates. The wires are brought to solder terminals on the other side of the plates through the holes of the glass posts. At those posts where they do not have to be connected to terminals, the wires are guided around the corners under the heads of common straight pins which are inserted into the glass tubes and epoxied on the back.

E. Sense Wire Electronics.

The sense wires are D.C. coupled to preamplifiers that carry their own high voltage blocking capacitors and are mounted outside the pressure vessel. The high voltage on each individual sense wire can be adjusted independently of all other wires.

The preamplifiers, designed around an op-amp/driver hybrid integrated circuit⁶⁾ have 35 nsec rise time, 2.5 μ sec decay time and 1 V/pC gain. These characteristics are well suited to the slow drift times and low sense wire gain of hydrogen. The blocking capacitors are encapsulated in epoxy to prevent electrical discharges and breakdown at the required high anode voltages. In the counting room, the preamp signals are amplified further using $\times 10$ linear amplifiers and are fanned out to discriminators for drift time measurements and to analog circuits for measurements of pulse height (dE/dx).

Drift times are measured by specially designed time digitizers which have 20 nsec least count resolution and multihit capability. Pulse heights are determined by six peak-detect/sample-and-hold circuits which are multiplexed to the appropriate analog signals at the time of the trigger. These circuits are designed from operational amplifiers with a high gain-bandwidth product (80 MHz) in order to respond uniformly to signals with the wide range of rise times expected from tracks of different drift times, angles and dE/dx .

F. Calibration Sources.

The drift time and gain stability of the TPC are monitored by ^{244}Cm α -sources positioned so as to leave tracks directly over the outer

wire, 4A', of each sense wire plate. The ionization produced by the emitted 5.8 MeV α -particles, which in 15 atm of H_2 have a range of 1.2 cm, is about 1,000 times that of minimum ionizing particles. This facilitates monitoring of the drift chambers even during start-up when the hydrogen is not yet purified.

The sources are deposited on the tips of 0.020" dia. wires which are mounted on lucite holders. One such assembly is positioned 2" above the sense wire while the other is placed 30" away, directly under the high voltage plate. The latter is viewed by a 1/8" dia. ZnS scintillation counter which serves to produce a zero-time reference for the measurement of the drift time. The ratio of the pulse height from the "far" source to that of the "near" source monitors the attenuation due to electron attachment.

V. HYDROGEN PURIFICATION

Electronegative impurities in the hydrogen gas absorb electrons and decrease their number as they drift towards the sense wires. For proper operation of the TPC, the oxygen impurity level in the hydrogen must be kept below 0.1 ppm. Other impurities from outgassing of the various materials inside the vessel must also be removed. For this purpose, a closed loop system was built that circulates the hydrogen through a purifier.

A schematic diagram of the gas system is shown in Figure 10. The purification elements are catalytic converters followed by molecular sieves. The converters contain palladium pellets which catalyze the burning of hydrogen with the oxygen to form water. Two such converters⁷⁾ with a total of

5 lbs of Pd are used in parallel in order to facilitate gas flow. The molecular sieves adsorb the water formed in the catalytic converters and other impurities present in the gas. They are 4A⁰ sieves⁸⁾ containing a total volume of 0.6 ft³ of sodium aluminosilicate. At a flow rate of 75 ft³ (three chamber volumes)/hr at 15 atm, the pressure-drop across the purification elements is approximately 2 psi.

The pump, which must operate in hydrogen at pressures of up to 300 psi, was designed and built at The Rockefeller University. The principle of the design is to house the bellows along with the driving motor inside a vessel which is maintained at the system pressure through a small orifice. Thus, the differential pressure across the bellows is small and a common, inexpensive pump⁹⁾ may be used inside the pump vessel.

Typically, after evacuating, flushing with helium and filling TREAD and the gas purification system with 0.99999 pure hydrogen, it takes about two hours for the TPC to operate efficiently.

Under steady state conditions, we find that the pulse height attenuation as a function of drift time is characterized by a time constant of ~ 1.8 msec. Since electron attachment to oxygen proceeds mainly through the reactions



the dependence of the attenuation time constant, τ , on the oxygen impurity level, f_{O_2} , is given by

$$\tau^{-1} = k \cdot N_{H_2} \cdot N_{O_2} = k \cdot N_{H_2}^2 \cdot f_{O_2} \quad (4)$$

where N is the gas density. Using the measured value of the 3-body attachment coefficient for thermal electrons¹⁰⁾, $k = (4.8 \pm 0.3) \times 10^{-31} \text{ cm}^6 \text{ sec}^{-1}$, we estimate that the oxygen impurity level during our steady state operation is $\lesssim 1$ part in 10^8 .

VI. HYDROGEN SAFETY

Because hydrogen gas is explosive and embrittles certain metals, special precautions must be taken in constructing a hydrogen pressure vessel. The Type 304 stainless steel and the Type A515 steel which were used in constructing TREAD and the pump vessel are immune to hydrogen embrittlement under our operating conditions. Both vessels are built to ASME Code Rules with a design pressure of 300 psi. Items incorporating non-standard ASME materials (lightpipes, electrical feed-through plugs) were tested hydrostatically to 1500 psi.

The vessel endcaps are covered with inerting hoods which maintain all feed-through plugs, electrical connections to the vessel, and photomultiplier bases in a nitrogen atmosphere. All power supplies are interlocked to the inerting hood pressure and to flammable gas detectors on the inerting hood exhaust system.

The beryllium window, due to its brittleness, was considered to be the most vulnerable part of the TREAD vessel. As discussed in Section III, special care was taken in mounting the window so as to decouple it from the endcaps which bend by as much as 2.5 mrad when the vessel is pressurized to 15 atm. As an additional precaution, a "flapper valve", designed¹¹⁾ to close

automatically by the escaping gas in the event of a window failure, is mounted in front of the window (see Fig. 4). From tests on a 12" dia. $\times$ 36" long vessel, in which rupture discs were allowed to burst at 250 psi, we estimate that only about 1% of the hydrogen gas will escape from TREAD in the event of such a failure.

VII. SENSE WIRE GAIN

The sense wire gain in hydrogen was measured, prior to building TREAD, in a simple proportional counter consisting of an anode wire stretched along the axis of an 0.5" I.D. aluminum cylinder. Two parallel "flats" milled on the cylinder wall provided thin windows to allow triggering on minimum ionizing electrons from a β -source. Measurements were carried out with 20 μ and 50 μ diameter sense wires at pressures from 5 to 15 atm.

The sense wire gain, G , may be calculated from the expression¹²⁾

$$\ln G = \int_{r_1}^{r_2} \alpha(r) dr \quad (5)$$

where α , the inverse of the electron mean free path for ionization (first Townsend coefficient), is a function of the pressure p and of the reduced electric field strength, $E(r)/p$. The integral is evaluated along the path of the electric field lines from the surface of the anode to that of the cathode.

Hydrogen ionization coefficients, α/p , have been measured by Rose¹³⁾ in the region $0.5 < p < 45$ torr and $15 < E/p < 1000$ V $\cdot$ cm⁻¹ $\cdot$ torr⁻¹. Rose's data are represented well by the simple formula

$$\alpha/p = a e^{-bp/E} \quad (6)$$

where $a = 5.1 \text{ cm}^{-1} \cdot \text{torr}^{-1}$ and $b = 138.8 \pm 0.4 \text{ V} \cdot \text{cm}^{-1} \cdot \text{torr}^{-1}$. Our measurements of gain in the region $5 < p < 15 \text{ atm}$ and $E/p \lesssim 90 \text{ V} \cdot \text{cm}^{-1} \cdot \text{torr}^{-1}$ are in good agreement with values calculated from Eq. (5) using α/p given by Eq. (6). This is shown in Figure 11 where our data on sense wire voltage versus pressure at fixed gain are compared to curves calculated in this manner.

The maximum gain just before electrical breakdown was found to be in the range $2\text{--}5 \times 10^4$, approximately independent of pressure or sense wire diameter. In Figure 12, breakdown voltages at various pressures measured with the 35μ dia. wires of TREAD are compared with constant gain curves calculated from Eq's. (5) and (6). These results show that, for our configuration and within our pressure range, the maximum obtainable gain is approximately constant and equal to a few $\times 10^4$.

VII. DRIFT VELOCITY

The electron drift velocity in hydrogen was measured in TREAD using the α -source monitors described in section IV-F. Our data at pressures from 24 to 220 psi are shown in Figure 13 along with other measurements¹⁴⁾ performed at lower pressures. The drift velocity is plotted as a function of E/p , the ratio of the drift field to the hydrogen gas pressure. The line through the data points in the region $0.3 < E/p < 3 \text{ kV} \cdot \text{m}^{-1} \cdot \text{psia}^{-1}$ represents a fit to the form

$$v_D = v_0 (E/p)^{b+c \ln(E/p)} \quad (7)$$

which parametrizes the drift velocity around $E/p = 1 \text{ kV m}^{-1} \text{ psia}^{-1}$, close to our normal operating conditions. We find $v_0 = 4.82 \pm 0.10 \text{ mm}/\mu\text{sec}$, $b = 0.6$ and $c = -0.1$. The error in v_0 is the variance obtained among data sets of different pressures. Our results show that density corrections to the drift velocity¹⁵⁾ in the pressure range $24 < p < 220 \text{ psi}$ are $\leq 2\%$.

VIII. SPATIAL RESOLUTION

The spatial resolution of the TPC operating at 15 atm was measured with cosmic ray tracks which triggered TREAD on diagonally opposite counters. Each half of the track on either side of the TPC axis was fit independently to a straight line. The spatial resolution for a particular wire was obtained by measuring the difference of the position recorded by the wire from the position predicted by the fit.

Figure 14 shows the resolution as a function of drift distance for wire 3A. The line is a fit to the form

$$\sigma^2 = \sigma_0^2 + \sigma_1^2 \left(\frac{Z}{1 \text{ cm}} \right) \quad (8)$$

We find $\sigma_0 = 123 \pm 5 \mu\text{m}$ and $\sigma_1 = 22 \pm 1 \mu\text{m}$. The value of σ_0 depends on the sense wire discriminator threshold. The term proportional to Z is due to electron diffusion. The diffusion width along the drift direction, calculated from known transport coefficients¹⁶⁾ in H_2 , is $\sigma_D^2 = (68 \mu\text{m})^2 \left(\frac{Z}{1 \text{ cm}} \right)$. From statistics, for the sense wire threshold used in the cosmic ray data,

we would then expect $\sigma_1 = 0.3 \times \sigma_D = 21 \mu\text{m}$, in excellent agreement with our measurement.

Figure 15 shows the residuals of wire 3A obtained from tracks distributed through the entire drift distance. The curve represents a gaussian fit to the data. The width of $\pm 185 \mu\text{m}$ is consistent with what one expects for tracks drifting on the average through one half of the 75 cm long drift space (see Fig. 14).

The resolution in the polar angle θ was obtained directly by comparing the angle of the fit on one half of each track to the fit on the other half. The r.m.s. width of the distribution of the difference between the two angles was divided by $\sqrt{2}$ and the result, σ_θ , which represents the resolution in the measurement of each angle, is plotted as a function of drift distance in Figure 16. For a track drifting from the middle of the chamber, the resolution is about ± 4.5 mr. On the basis of the spatial resolution alone (see Fig. 15), the angular resolution expected with our sense wire configuration (see Fig. 5) is ± 1.5 mr. Distortion of the tracks as they drift towards the sense wire plate increases this width. A measure of the distortions in our TPC is provided by the difference of the angles obtained for the two halves of each cosmic ray track. Figure 17 shows this difference. The overall offset of ~ 3.25 mr in $(\theta_1 - \theta_2)/2$ shifts the angle but does not affect the angular resolution. The spread around this offset broadens the resolution since, in general, the cosmic ray tracks have large angles with respect to the vertical direction and therefore the two halves of each track suffer different amounts of distortion. Because of these distortions,

the slope of σ_θ^2 versus Z is larger than the slope expected from electron diffusion. This is not the case however with the slope of σ_Z^2 versus Z (see Fig. 14), since the spatial resolution, from the way it was obtained, is much less sensitive to these distortions.

Figure 18 shows a sense wire pulse height spectrum for cosmic ray tracks distributed through the entire drift chamber. The curve is a Landau distribution fit to the data.

LX. PERFORMANCE IN THE BEAM

Experiment E-612 ran in the tagged photon beam of Fermilab during the months of March, April and May of 1981. TREAD was filled with hydrogen gas at 220 psi and was operated with a drift field of 1.73 kV/cm (130 kV over 75 cm). No problems were encountered during this run. In particular, the purification system performed well without pump failures or any need to replace the molecular sieves. The high voltage system also performed satisfactorily. Although a drift voltage as high as 180 kV was applied occasionally for test purposes, we chose to run conservatively at 130 kV to avoid high voltage problems.

During the beam spill, particles produced in the beam halo loaded the drift space with unwanted tracks. Since we were interested only in recoil protons with dE/dx six to ten times that of minimum ionizing particles, we purposely made our TPC inefficient for minimum ionizing tracks by lowering the sense wire gain to 1.5×10^2 .

At this gain, only ≥ 5 times minimum ionizing tracks triggered our discriminators. Under these conditions, the total sense wire current during the beam spill was ~ 20 nA.

The photon beam data are presently being analyzed. The results presented below are from a short test run in which a 170 GeV π^- beam was brought down the beam line and data were collected on the reaction

$$\pi^- + p \rightarrow X + p \quad (9)$$

Unlike the tagged photon beam where the resolution of the photon momentum depends on the resolutions and calibrations of the counters in the tagging system, the pion momentum is fixed to sufficiently good accuracy by the beam line magnets. Thus, the missing mass resolution for $\pi^- p \rightarrow Xp$ is mainly due to the uncertainties in the kinetic energy and the polar angle of the recoil proton, quantities that are measured in TREAD. Furthermore, the pion data may be compared directly with data obtained¹⁷⁾ in experiment E-396 in which the same technique was used except that the recoil proton angle was measured with small plane drift chambers rather than a TPC.

As in the photon beam, the sense wire gain was set at 1.5×10^2 and the beam intensity was adjusted so that the total sense wire current was again ~ 20 nA. These conditions were chosen to be the same for the two beams so that the pion data could also serve as a calibration of the photon data. Figure 19 shows a scatter plot of dE/dx versus kinetic energy for recoil particles. The hyperbolic band is due to protons. The product of dE/dx times T is proportional to the mass of the recoil. A histogram of recoil masses is shown in Figure 20. Recoil protons were selected by a

cut in recoil mass. The missing mass, calculated by using Eq. (2), is shown in Figure 21. Elastic events are centered at $M_x^2 = m_\pi^2 \approx 0.02 \text{ (GeV)}^2$. The events at higher positive masses are due to diffraction dissociation. For comparison, Figure 22 shows a similar histogram obtained in E-396. The mass resolution of the elastic peak in E-612 is equally good to that in E-396 where, as mentioned above, plane drift chambers rather than a TPC were used to measure the recoil angle. The width of the elastic peak can be accounted for by the uncertainty in t , $\Delta t = \pm 0.002 \text{ (GeV/c)}^2$, and an uncertainty in the angle of $\pm 5.5 \text{ mr}$. Multiple scattering contributes about $\pm 3.5 \text{ mr}$ to the angle uncertainty. The error due to measurement, $[(5.5)^2 - (3.5)^2]^{1/2} \approx 4.5 \text{ mr}$, is consistent with what was obtained in the cosmic ray tests (see Fig. 16). No detectable broadening of the angular resolution due to space charge effects was observed when operating TREAD in the beam.

X. CONCLUSION

We have constructed a high pressure hydrogen time projection chamber consisting of two drift regions each 45 cm in diameter and 75 cm long. The chamber was tested with cosmic rays and was operated in a high energy particle beam for several months. No problems were encountered during the run. The spatial resolution of the chamber is, on the average, $\pm 185 \text{ } \mu\text{m}$ and the distortions over the entire drift region are $\leq 0.5 \text{ mm}$.

XI. ACKNOWLEDGMENTS

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We also wish to thank the Magnet Facility for building our magnet; Henry Koecher for the use of the Lab 6 facilities during the assembly and initial testing of TREAD; and the Fermilab ad hoc safety committee which, under chairman George Biallas, helped us develop a safe system.

REFERENCES

- 1) Model 300D/TJE, manufactured by Sensotec, Inc., Columbus, Ohio.
- 2) We used a commercial 200 kV power supply, Model RHR-200N100, manufactured by Spellman High-Voltage Electronics Corporation, Plainview, New York.
A 60 M Ω resistor in series with the 60 ft. long RG-220 high voltage cable provided a filter for the supply's 40 kHz ripple.
- 3) The metal film resistors were made with 1/8" thick leads to prevent corona discharge. We found that the electric field between the outer cage and the vessel wall (about 50 kV/cm) could permanently alter the values of these resistors by as much as 5%. Special conducting guards connected to one of the leads of each resistor were installed to reduce the electric field at the resistor.
- 4) For Type 304 steel, see A.W. Loginow and E.H. Phelps, CORROSION-NACE, Vol. 31, No. 11, November 1975, pp. 404-412. Type A515 steel is used in the construction of commercial hydrogen gas bottles.
- 5) Model LP-241, manufactured by Isotope Products Laboratories, Burbank, California.
- 6) Model TRA510, manufactured by LeCroy Research Systems, Spring Valley, New York.
- 7) Model D-200-1200, manufactured by Engelhard Industries, Union, New Jersey.
- 8) Model 461, manufactured by Matheson Gas Products, East Rutherford, New Jersey.
- 9) Model MB118, manufactured by Metal Bellows Corp., Sharon, Massachusetts.
- 10) H. Shimamori and Y. Hatano, Chem. Phys. Lett. 38, 242 (1976).
- 11) The flapper valve was designed by R. Currier of Fermilab, Batavia, Illinois.
- 12) J.S. Townsend, Phil. Mag. 3, 557 (1902).

- 13) D.J. Rose, Phys. Rev. 104, 273 (1956).
- 14) J.J. Lowke, Aust. J. Phys. 16, 115 (1963).
- 15) See discussion in L.G.H. Huxley and R.W. Crompton, *The Diffusion and Drift of Electrons in Gases*, J. Wiley, New York, 1974, pp. 358-364.
- 16) E.B. Wagner, F.J. Davis and G.S. Hurst, J. Chem. Phys. 47, 3138 (1967);
see also Ref. 15, pp. 615-624.
- 17) R.L. Cool, K. Goulianos, S.L. Segler, G. Snow, H. Sticker and S.N. White,
"Elastic Scattering of $p^{\pm}$, $\pi^{\pm}$ and $K^{\pm}$ on Protons at High Energies and
Small Momentum Transfer," (submitted to Phys. Rev. D); R.L. Cool,
K. Goulianos, S.L. Segler, H. Sticker and S.N. White, "Diffraction
Dissociation of $\pi^{\pm}$, $K^{\pm}$ and $p^{\pm}$ at 100 and 200 GeV/c," (submitted to
Phys. Rev. Lett.)

FIGURE CAPTIONS

- Fig. 1 : Experimental arrangement.
- Fig. 2 : Missing mass spectrum expected from $\gamma p \rightarrow Xp$ at 50 GeV.
- Fig. 3 : Fractional missing mass r.m.s. resolution $\Delta M_X^2 / M_X^2$ versus M_X^2/s for $\gamma p \rightarrow Xp$.
- Fig. 4 : TREAD - The Recoil Energy and Angle Detector.
- Fig. 5 : TPC sense wire arrangement and TREAD cross-sectional view.
- Fig. 6 : The drift field in the vicinity of a sense wire.
- Fig. 7 : A partially completed endcap assembly being installed on the TREAD vessel. The "outer cage" field shaping rings are clearly visible.
- Fig. 8 : A completed endcap assembly viewed from the high voltage side of the TPC. The sense wire plate at the center is surrounded by the scintillation counters.
- Fig. 9 : Beam window design.
- Fig. 10 : The hydrogen purification system.
- Fig. 11 : Sense wire voltage versus hydrogen gas pressure at gain of 10^4 . Our data, obtained with the simple proportional counter shown at the upper left corner of the figure, are compared to curves calculated using Eq's. (5) and (6) in the text.
- Fig. 12 : Sense wire breakdown voltage versus hydrogen gas pressure in TREAD (see upper left corner of figure) compared to fixed gain curves calculated using Eq's. (5) and (6) in the text.
- Fig. 13 : Electron drift velocity in hydrogen versus E/p . The curve represents an empirical fit (Eq. 7 in the text).
- Fig. 14 : Spatial resolution versus drift distance for wire 3A.

- Fig. 15 : Wire 3A residuals from cosmic ray tracks distributed through the entire 75 cm long drift space.
- Fig. 16 : Angular resolution versus drift distance (not corrected for distortions).
- Fig. 17 : The difference in the angle obtained from the two halves of each cosmic ray track (on either side of the TPC axis) plotted against the drift distance.
- Fig. 18 : Sense wire pulse height spectrum for cosmic ray tracks distributed through the entire drift space.
- Fig. 19 : Recoil particle energy loss, dE/dx , versus kinetic energy for $\pi^- p \rightarrow Xp$ at 170 GeV.
- Fig. 20 : The mass of the recoil particle divided by the mass of the proton, calculated from the energy loss dE/dx and the kinetic energy T for $\pi^- p \rightarrow Xp$ at 170 GeV.
- Fig. 21 : Missing mass squared distribution for $\pi^- p \rightarrow Xp$ at 170 GeV obtained in experiment E-612 using TREAD.
- Fig. 22 : Missing mass squared distribution for $\pi^- p \rightarrow Xp$ at 170 GeV obtained in experiment E-396 using small plane drift chambers.

EXPERIMENTAL ARRANGEMENT

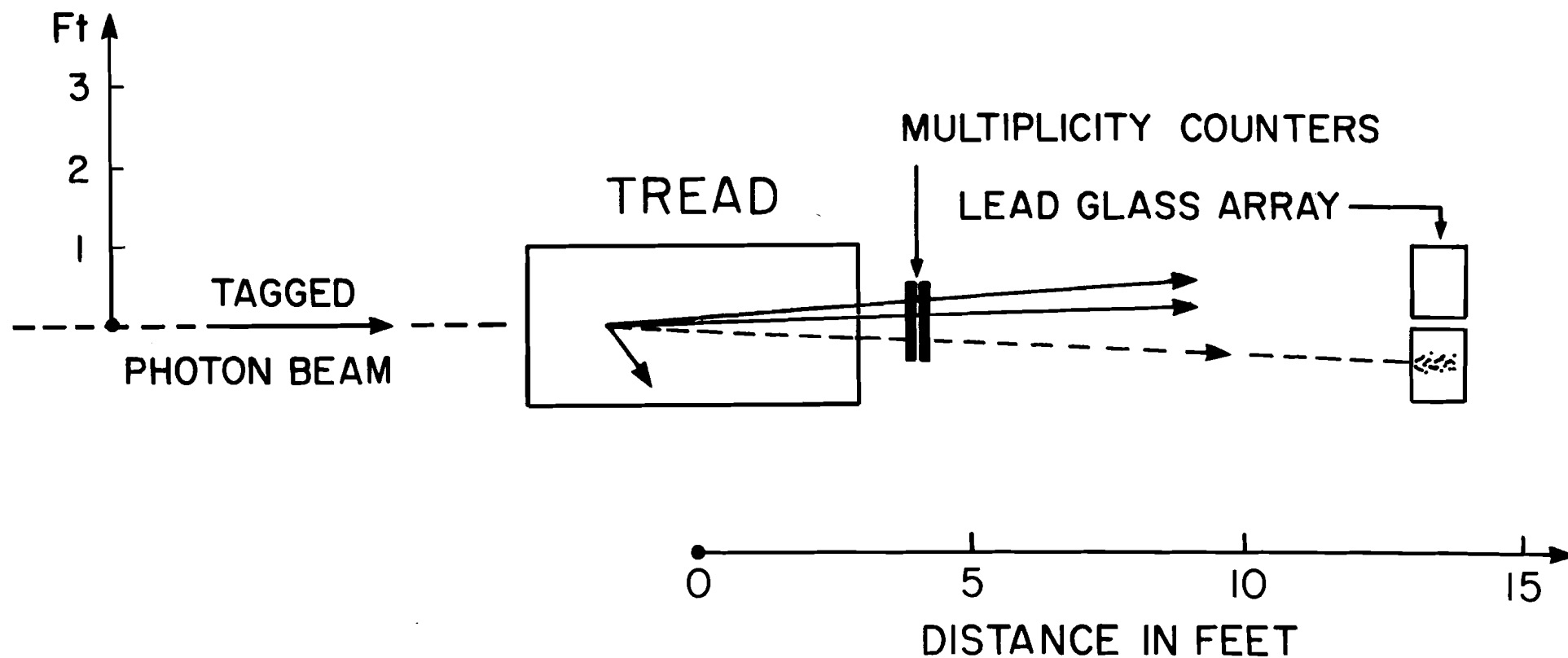
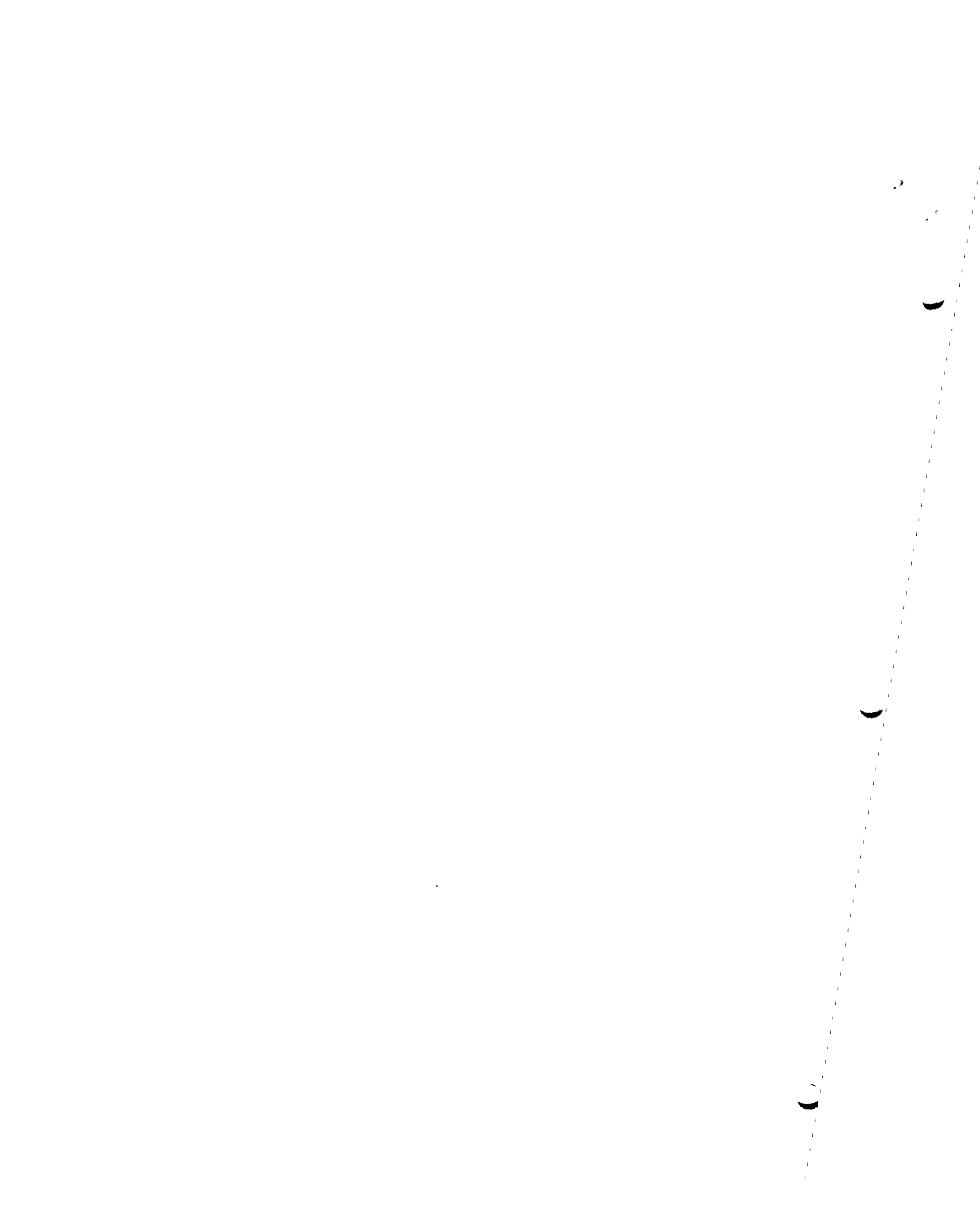


FIGURE 1



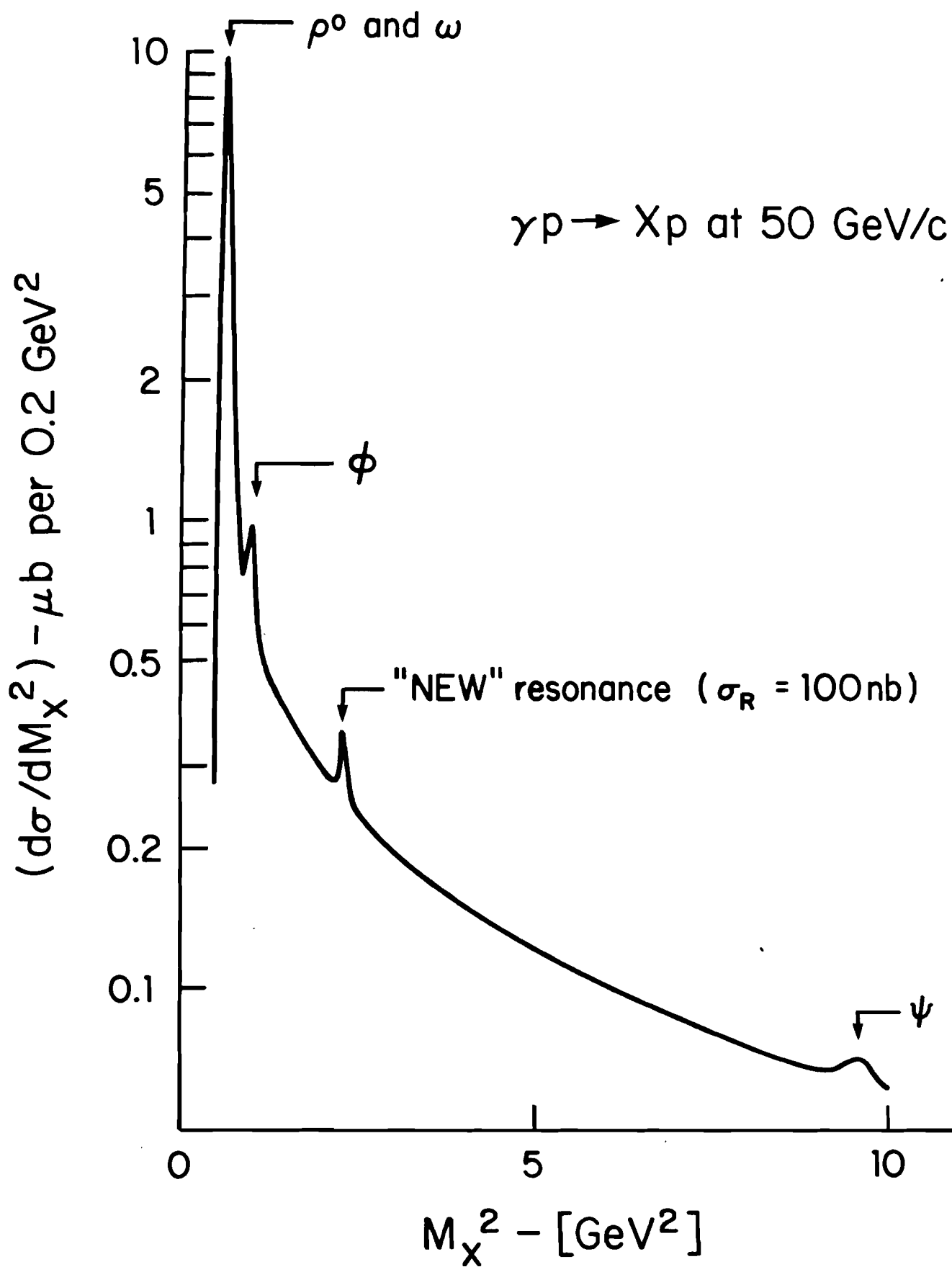
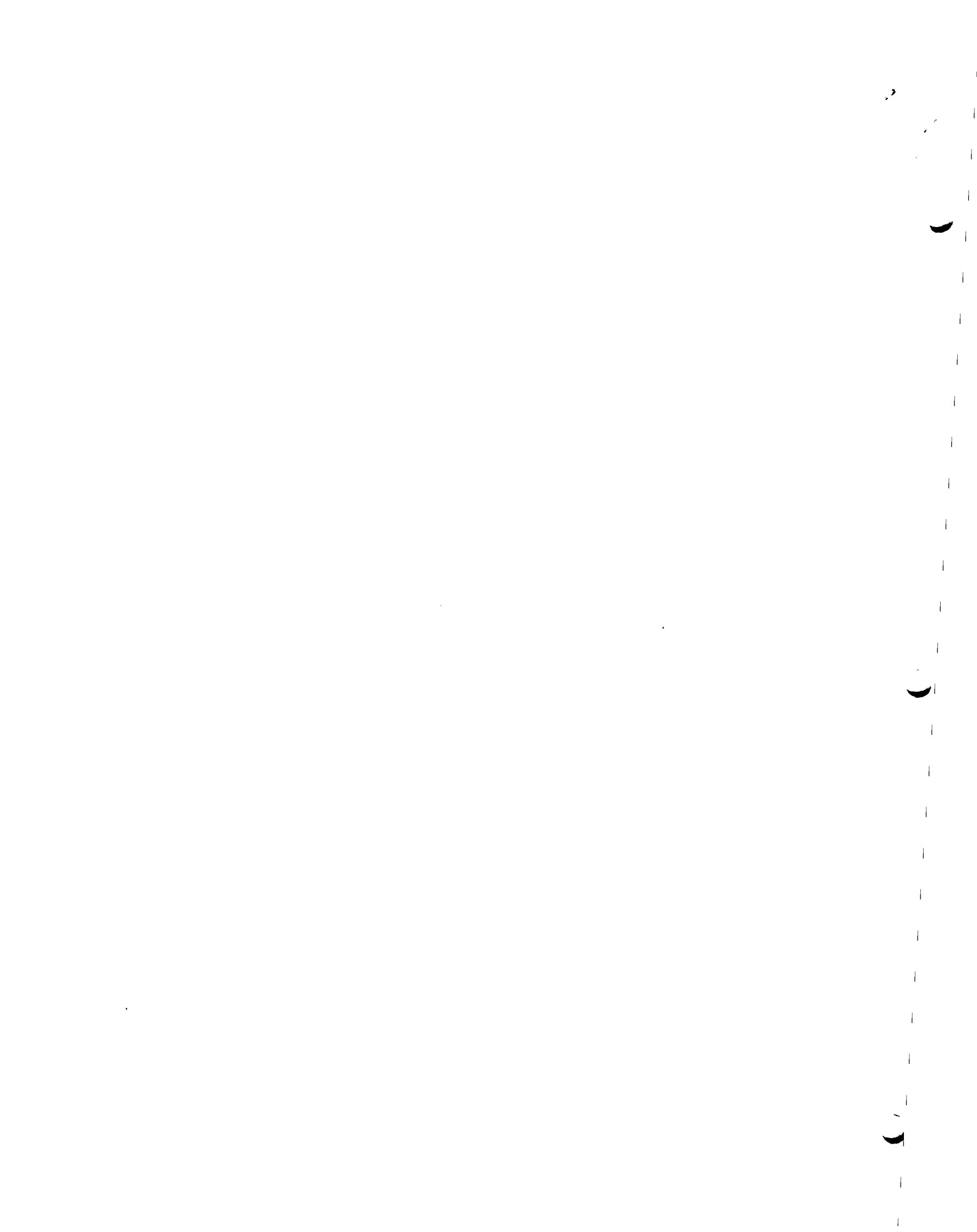


FIGURE 2



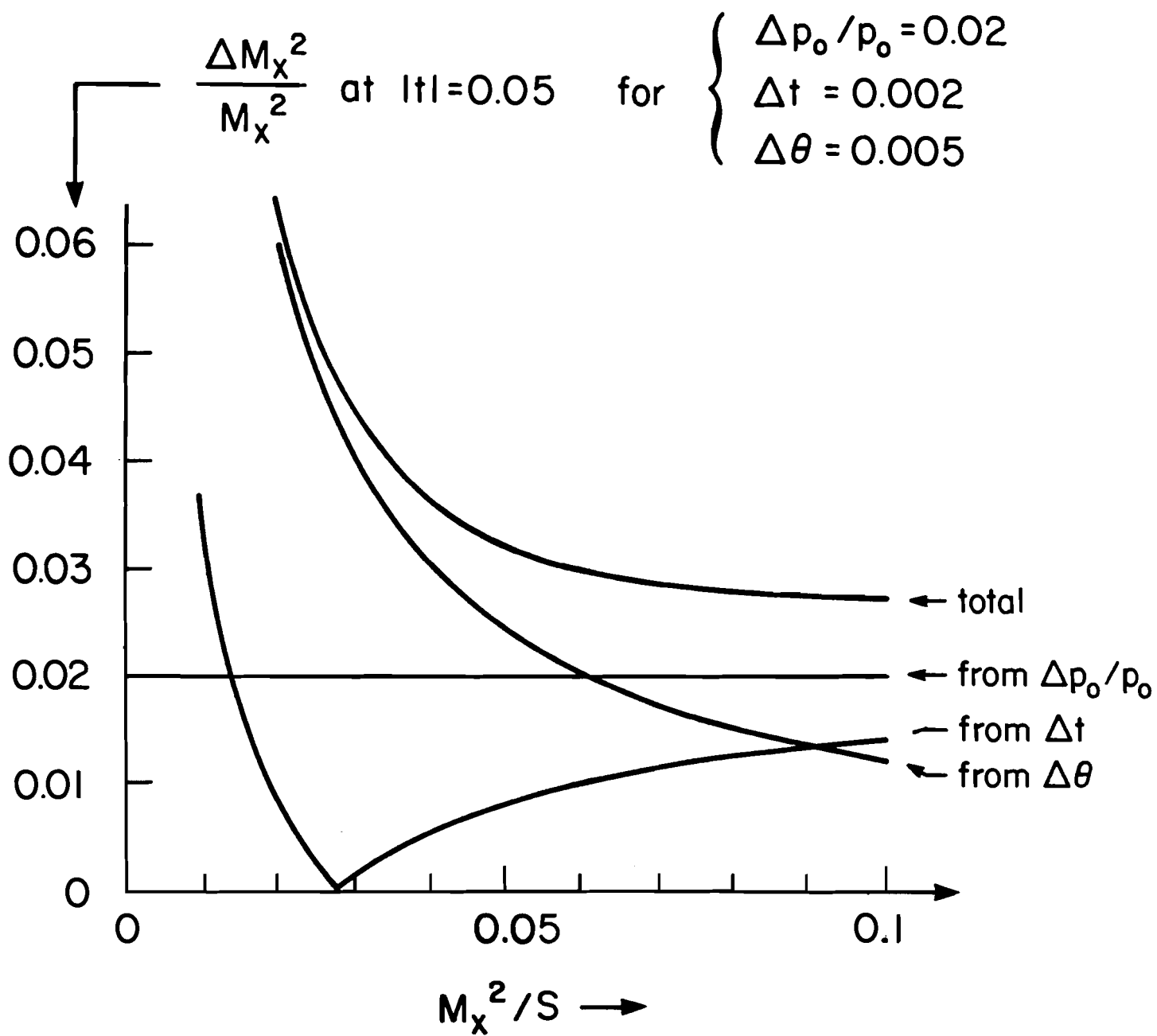


FIGURE 3

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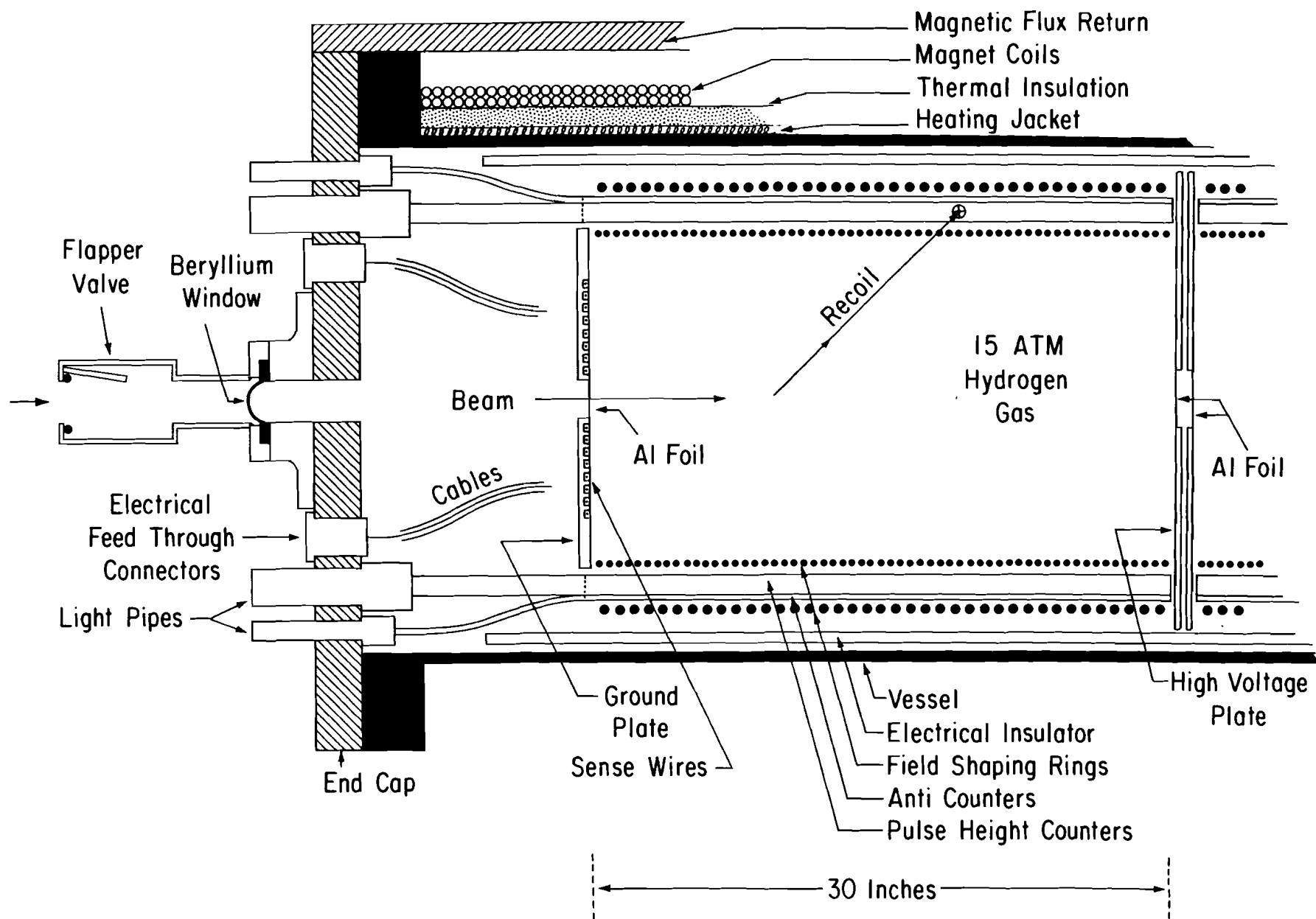


FIGURE 4

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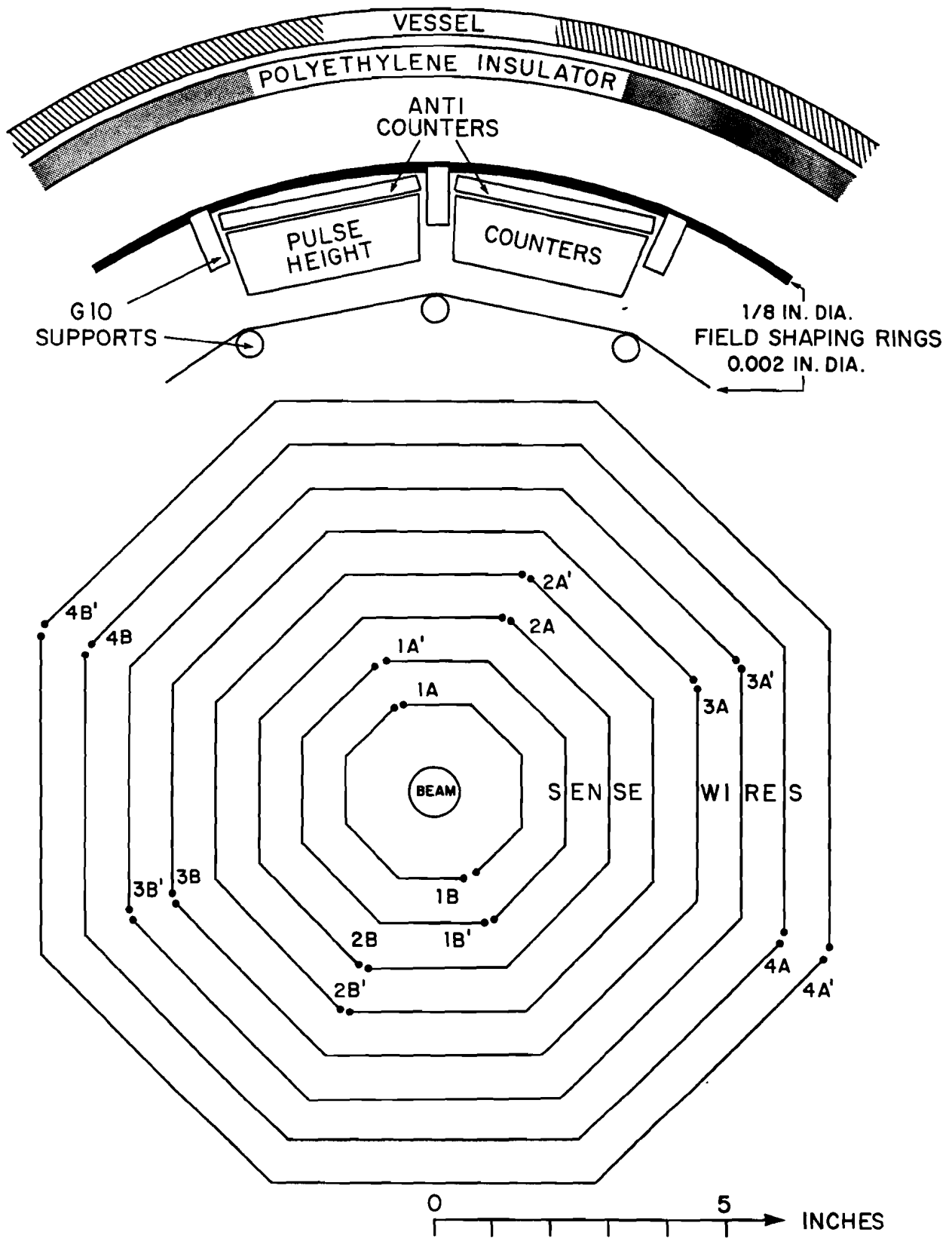


FIGURE 5

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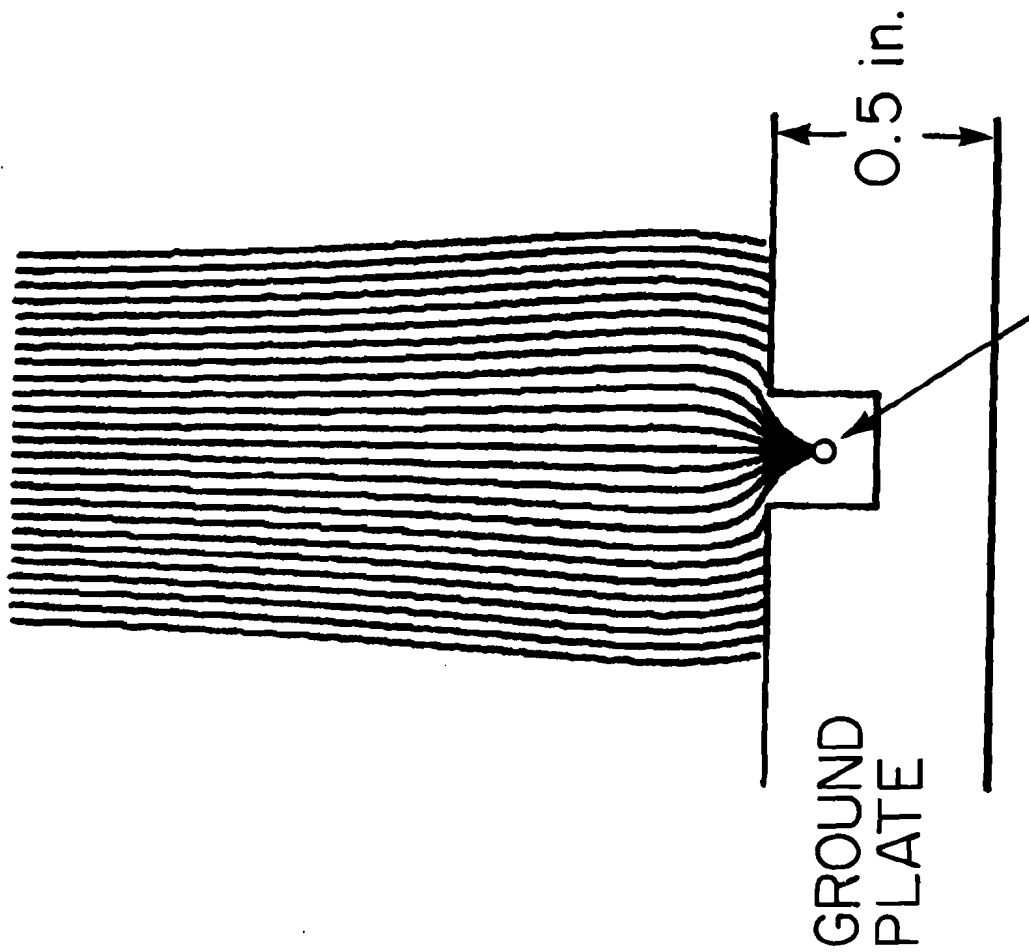
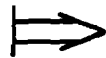
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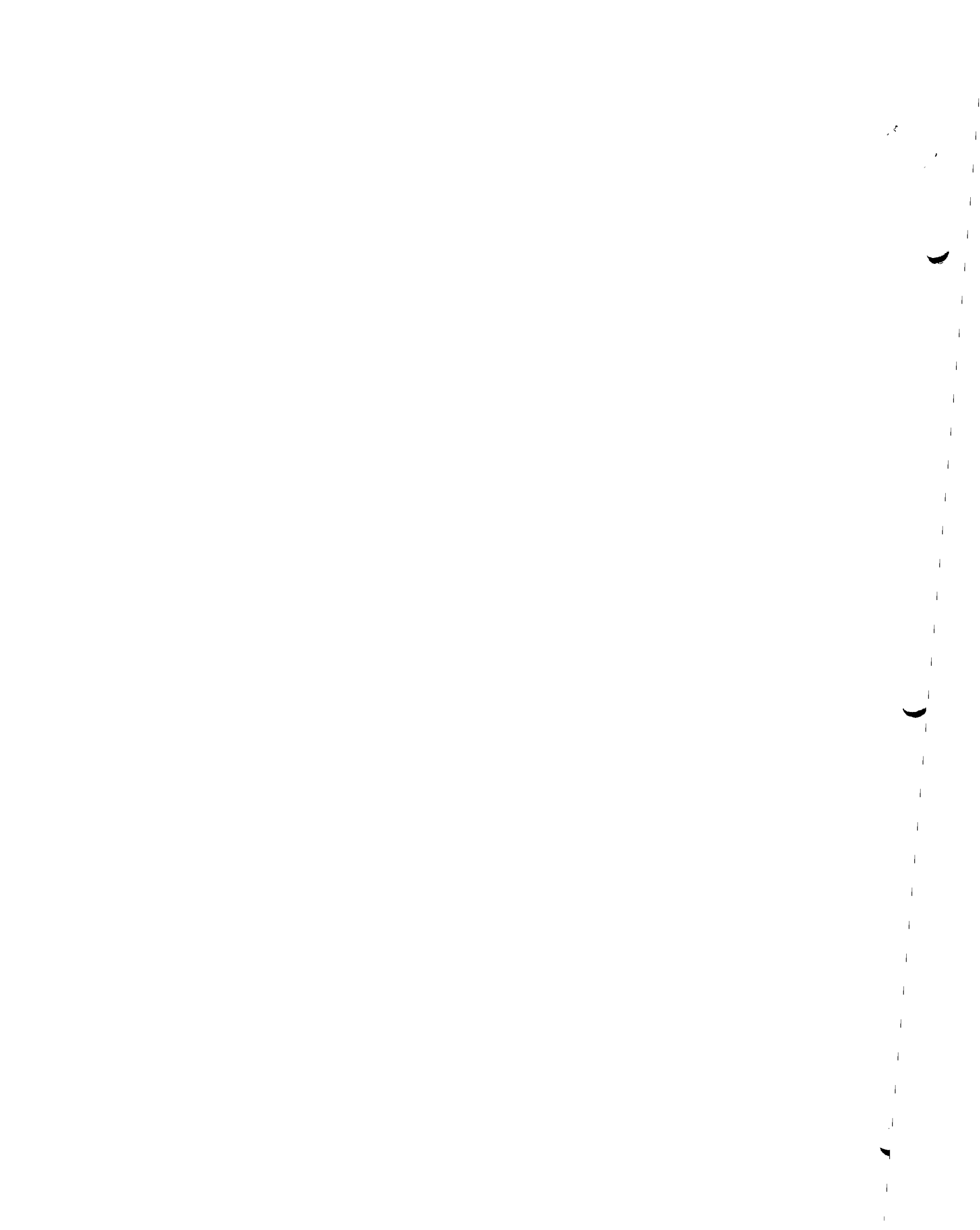
6

DRIFT FIELD
1.75 kV/cm



35 μ dia.
SENSE WIRE
at 7 kV

FIGURE 6



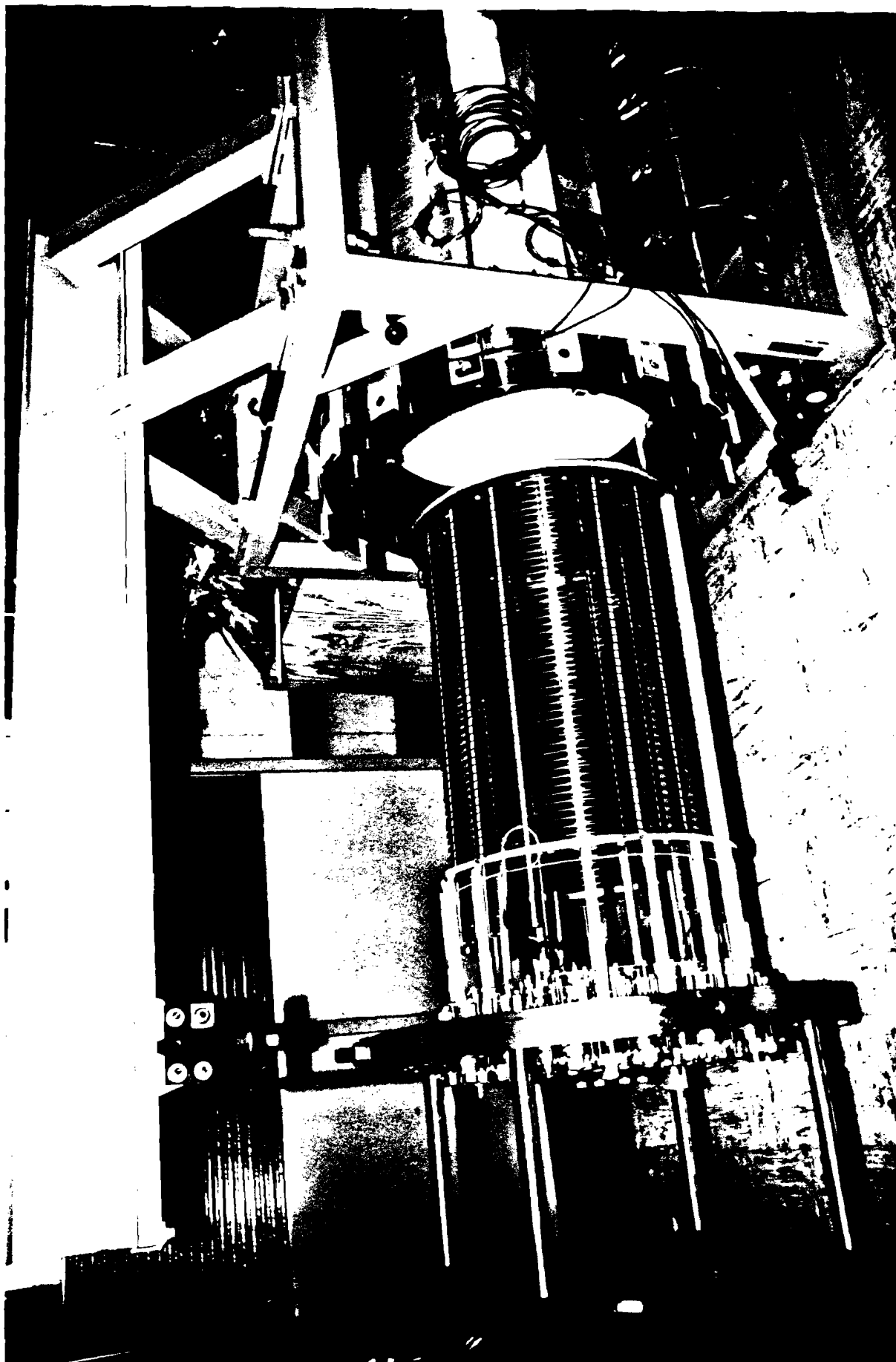


FIGURE 7

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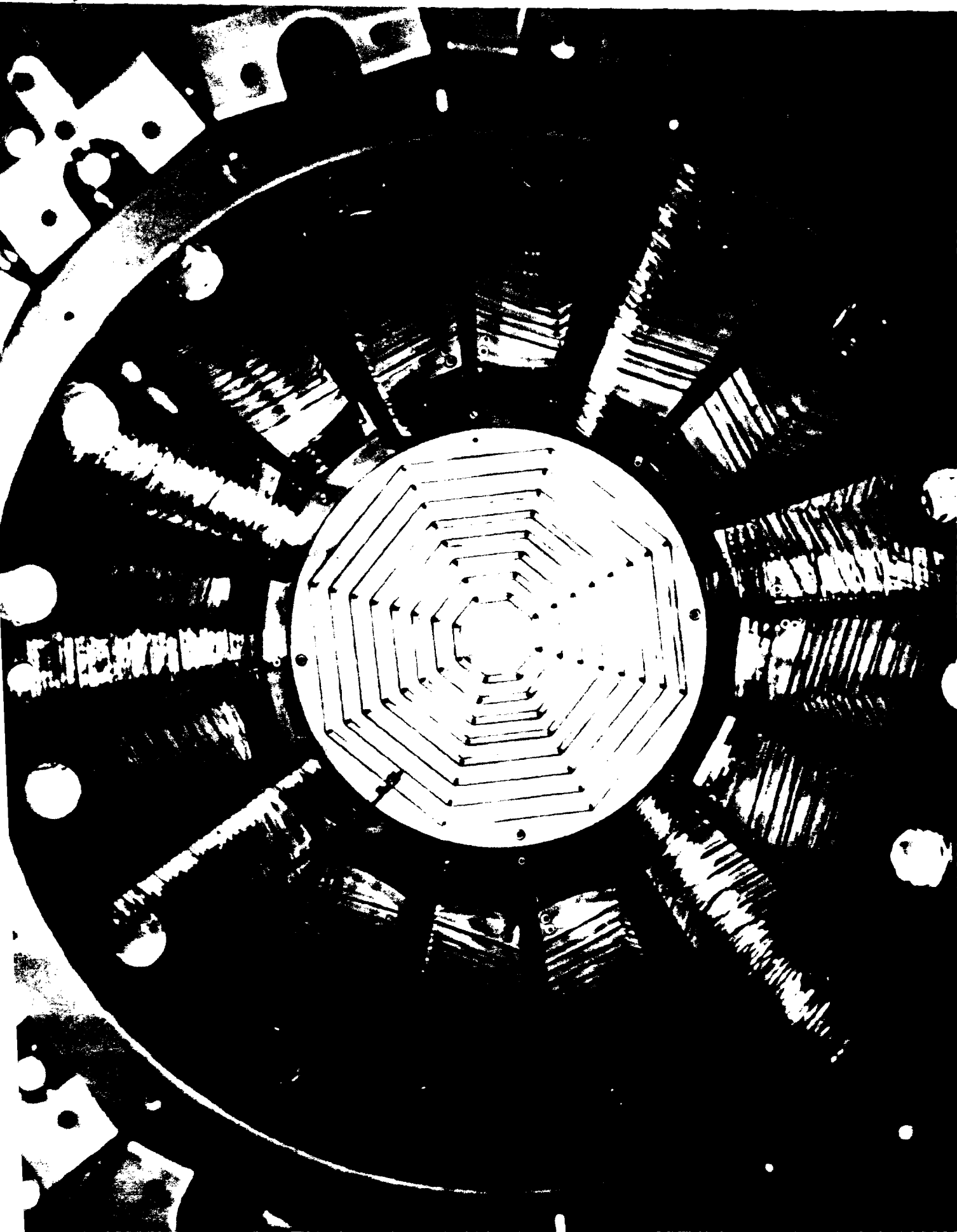


FIGURE 8

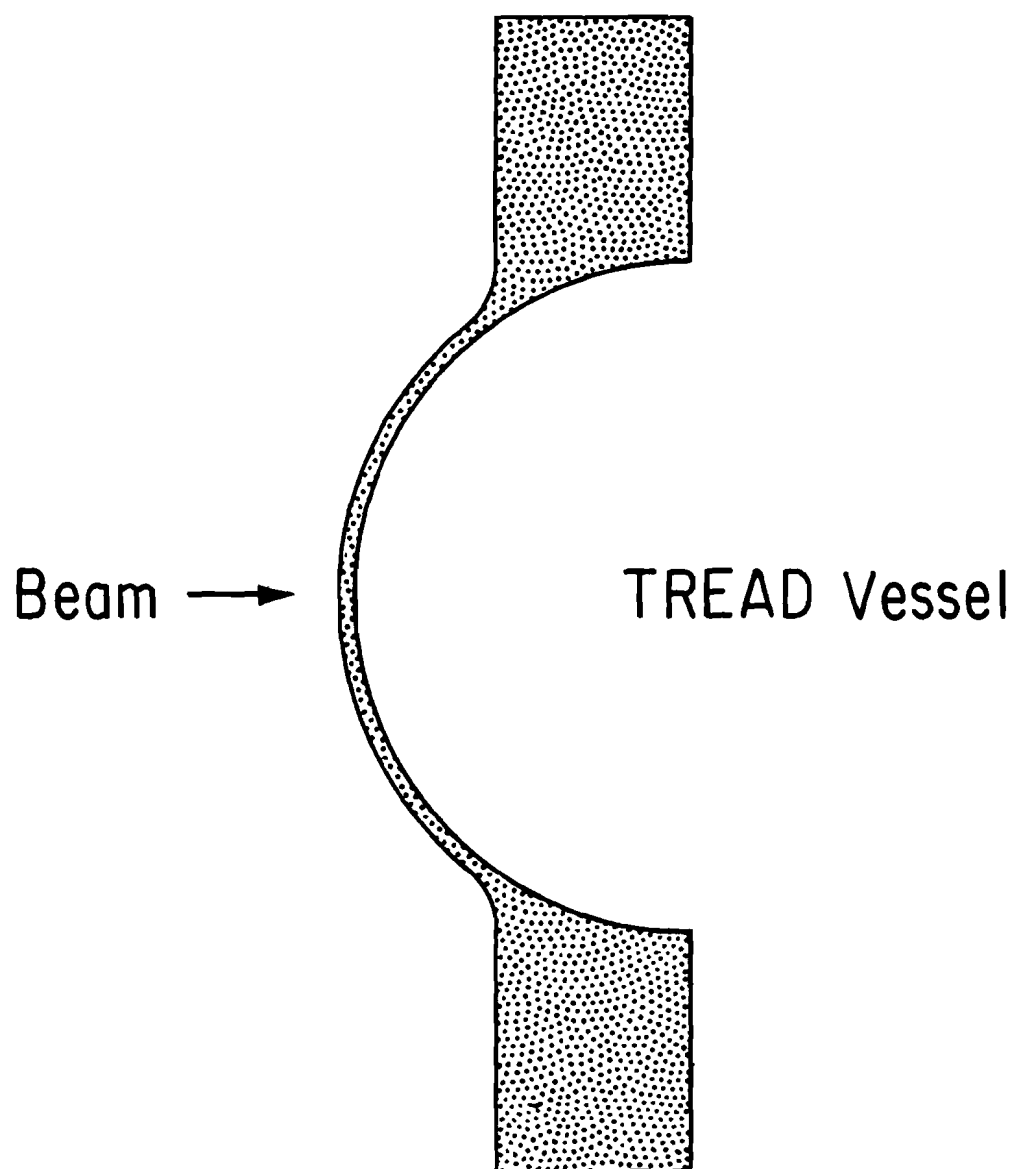
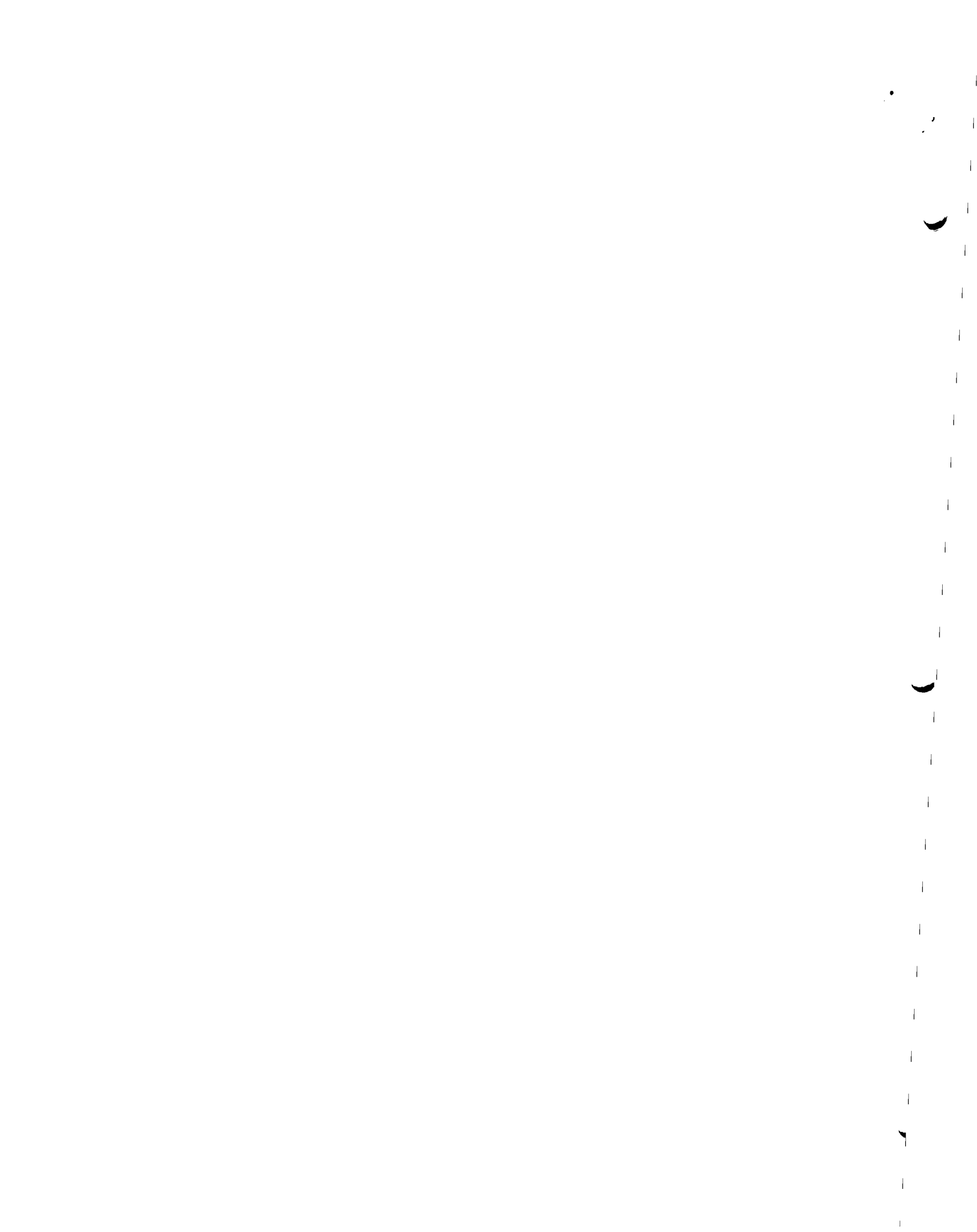


FIGURE 9



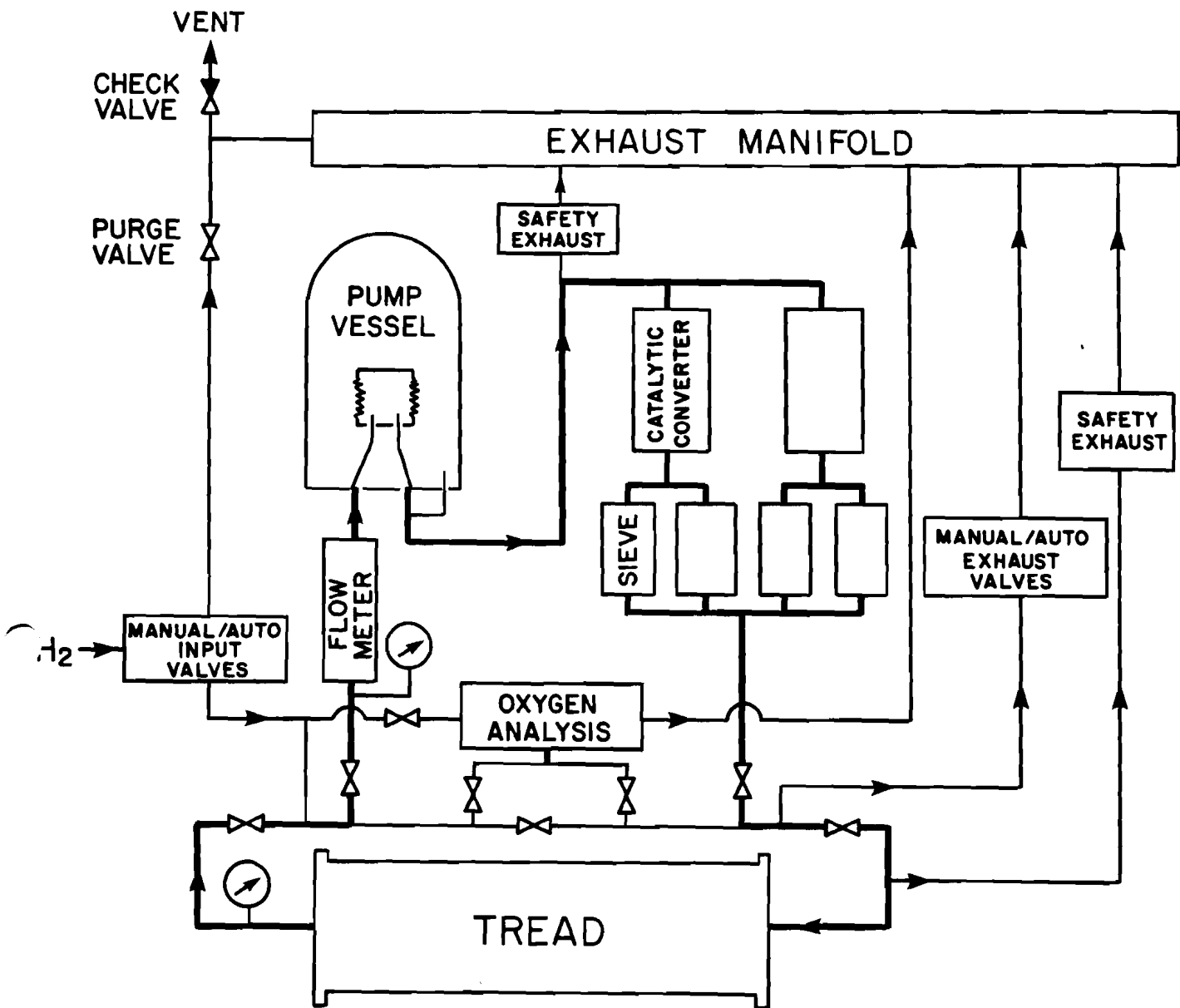


FIGURE 10

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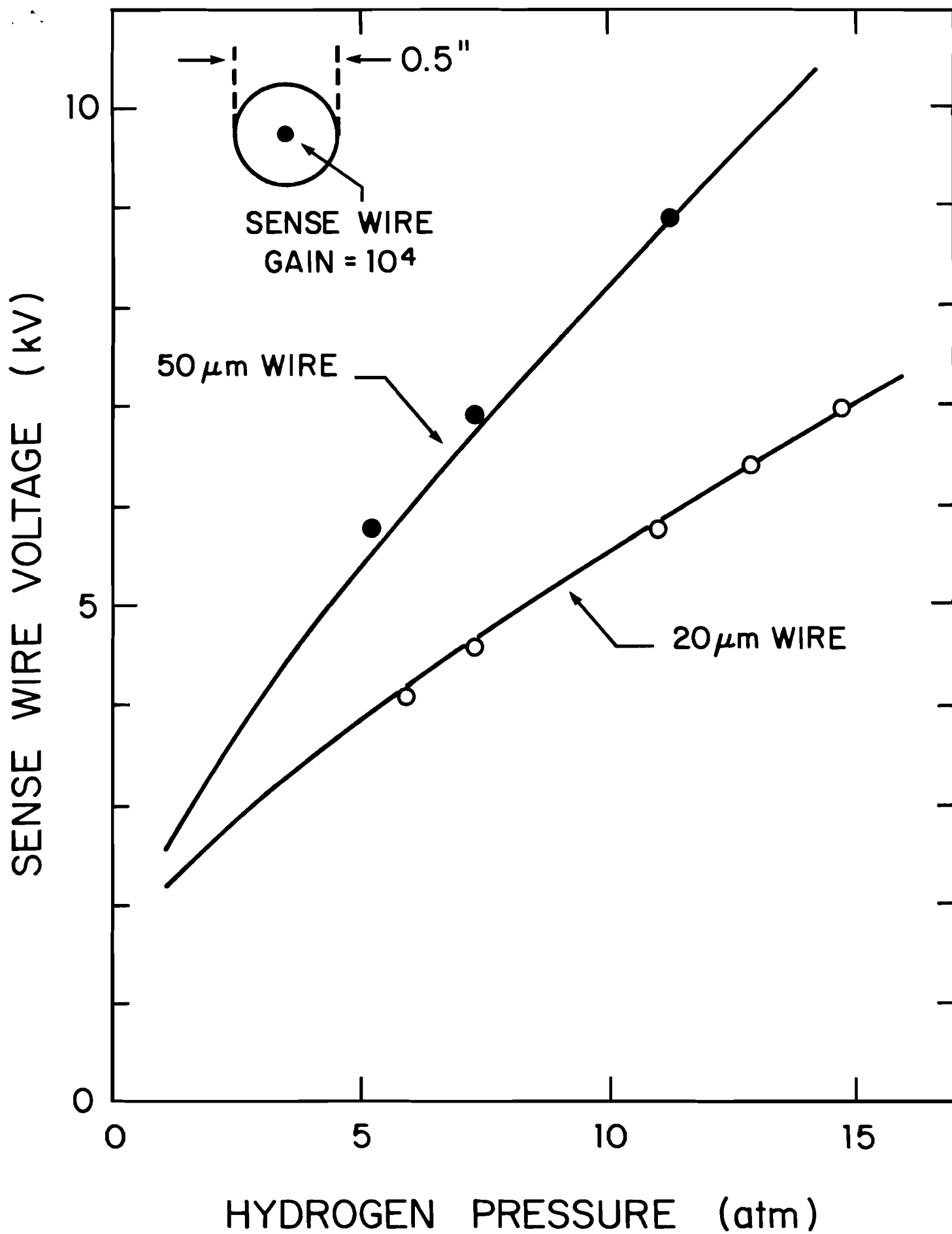


FIGURE 11

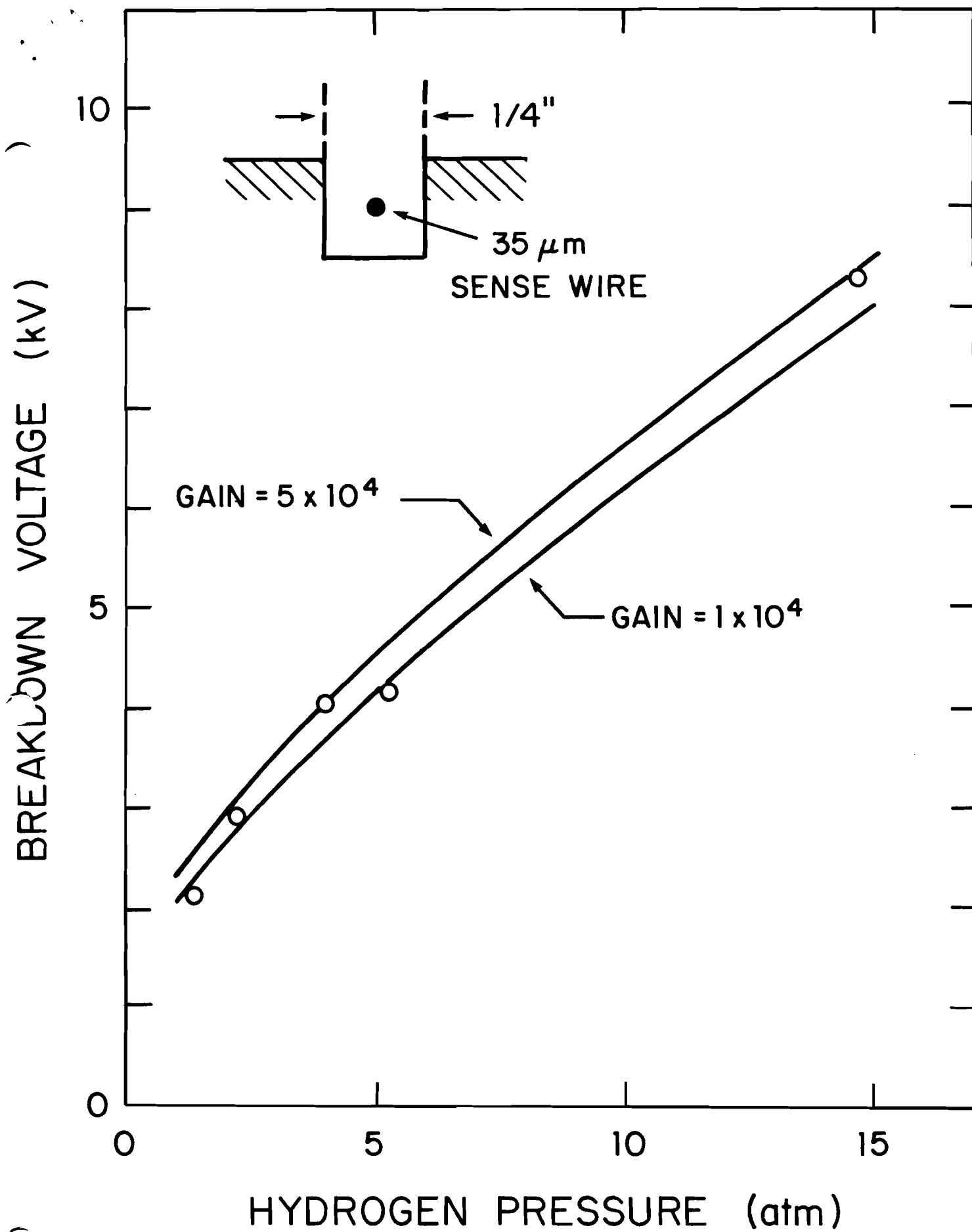


FIGURE 12

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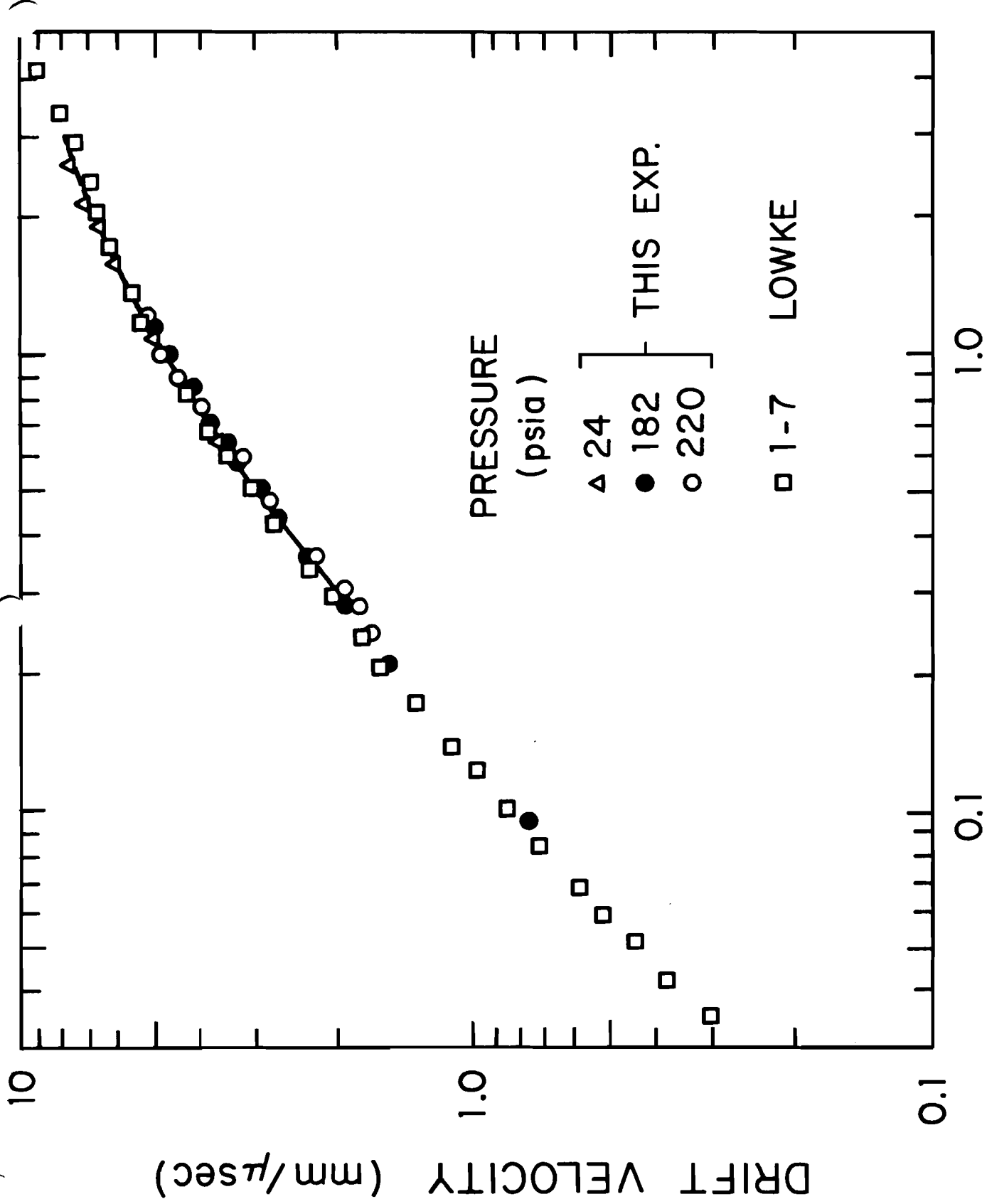


FIGURE 13

$$E/p \text{ (kV} \cdot \text{m}^{-1} \cdot \text{psia}^{-1} \text{)}$$

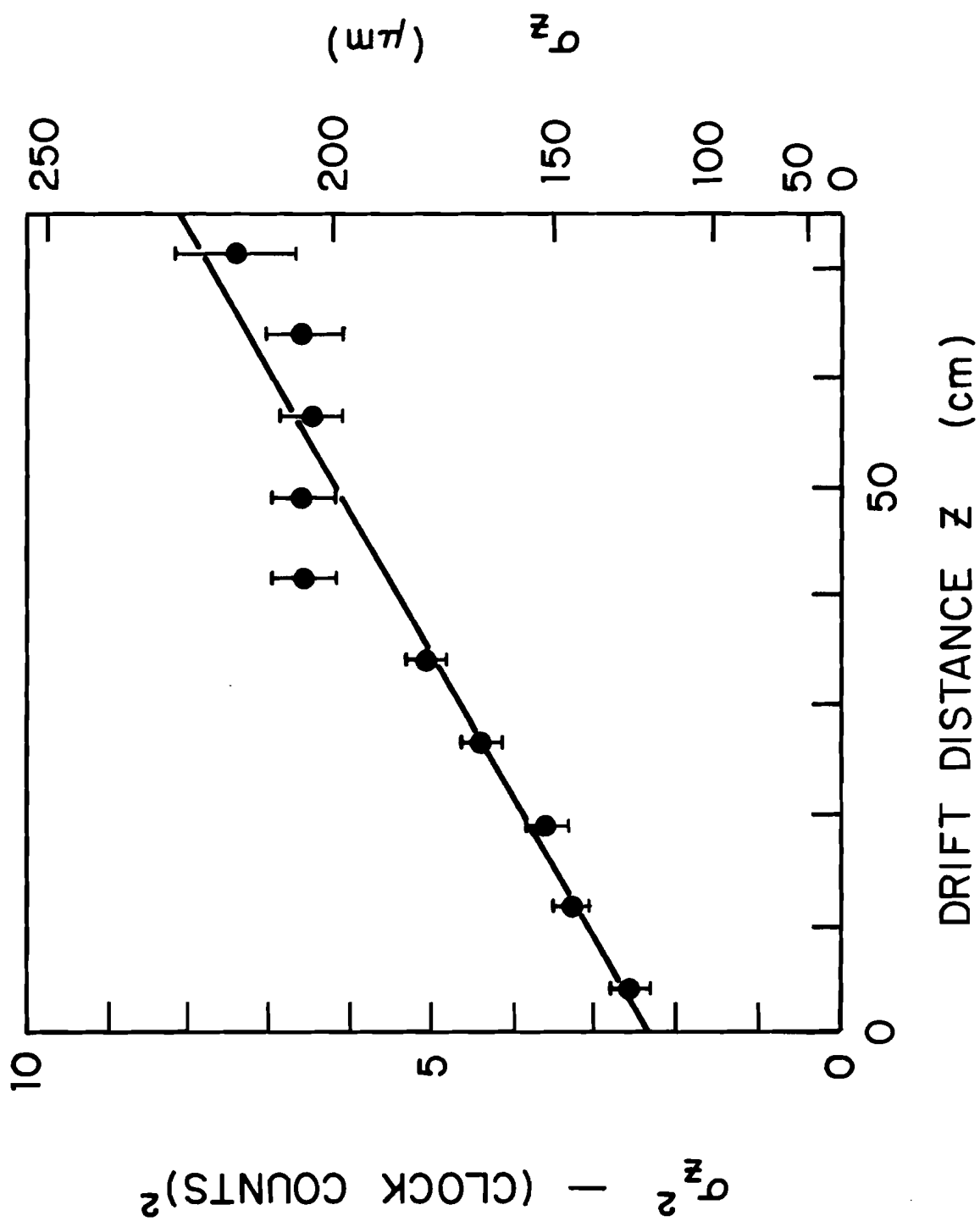


FIGURE 14

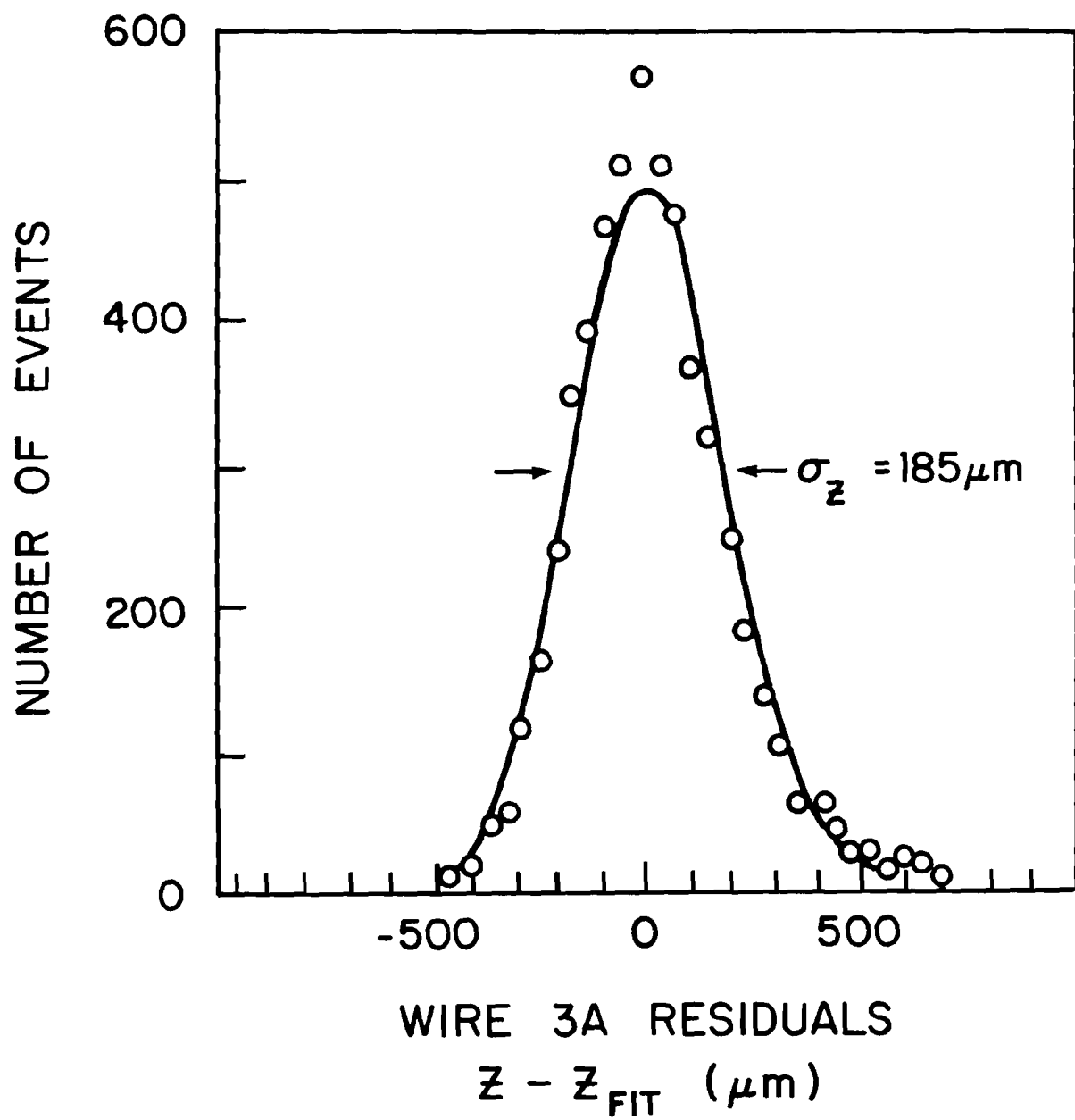


FIGURE 15

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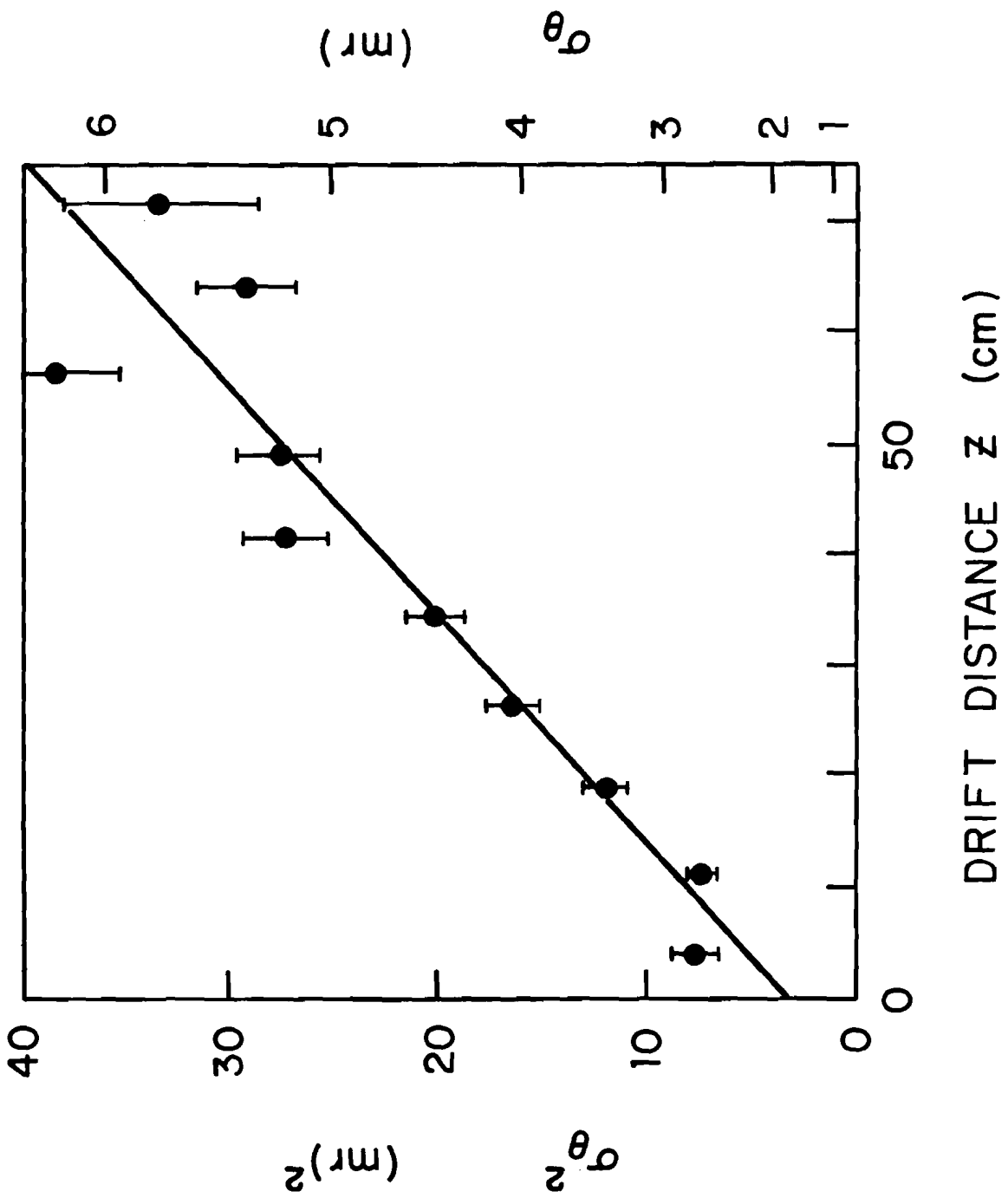


FIGURE 16

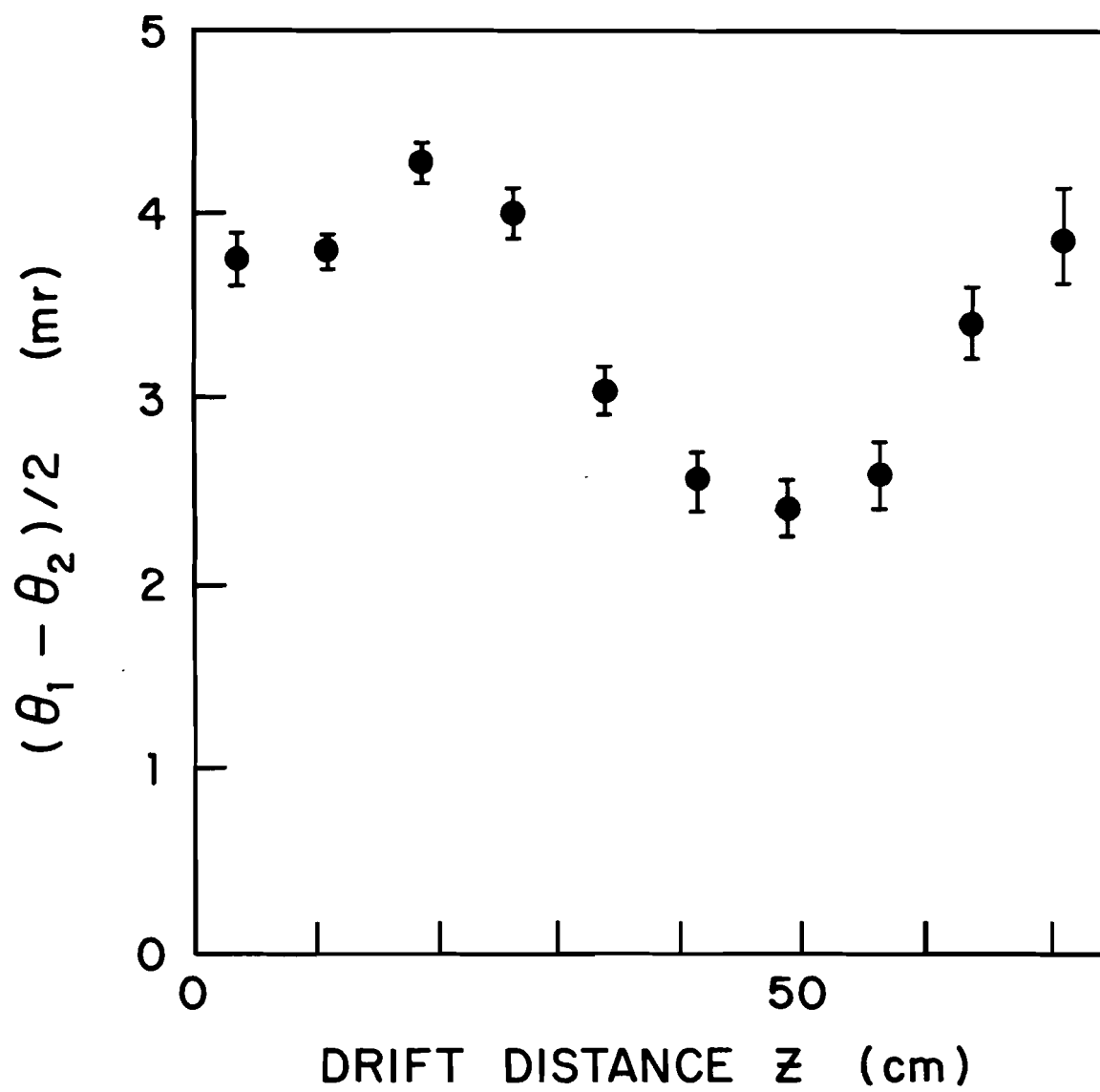


FIGURE 17

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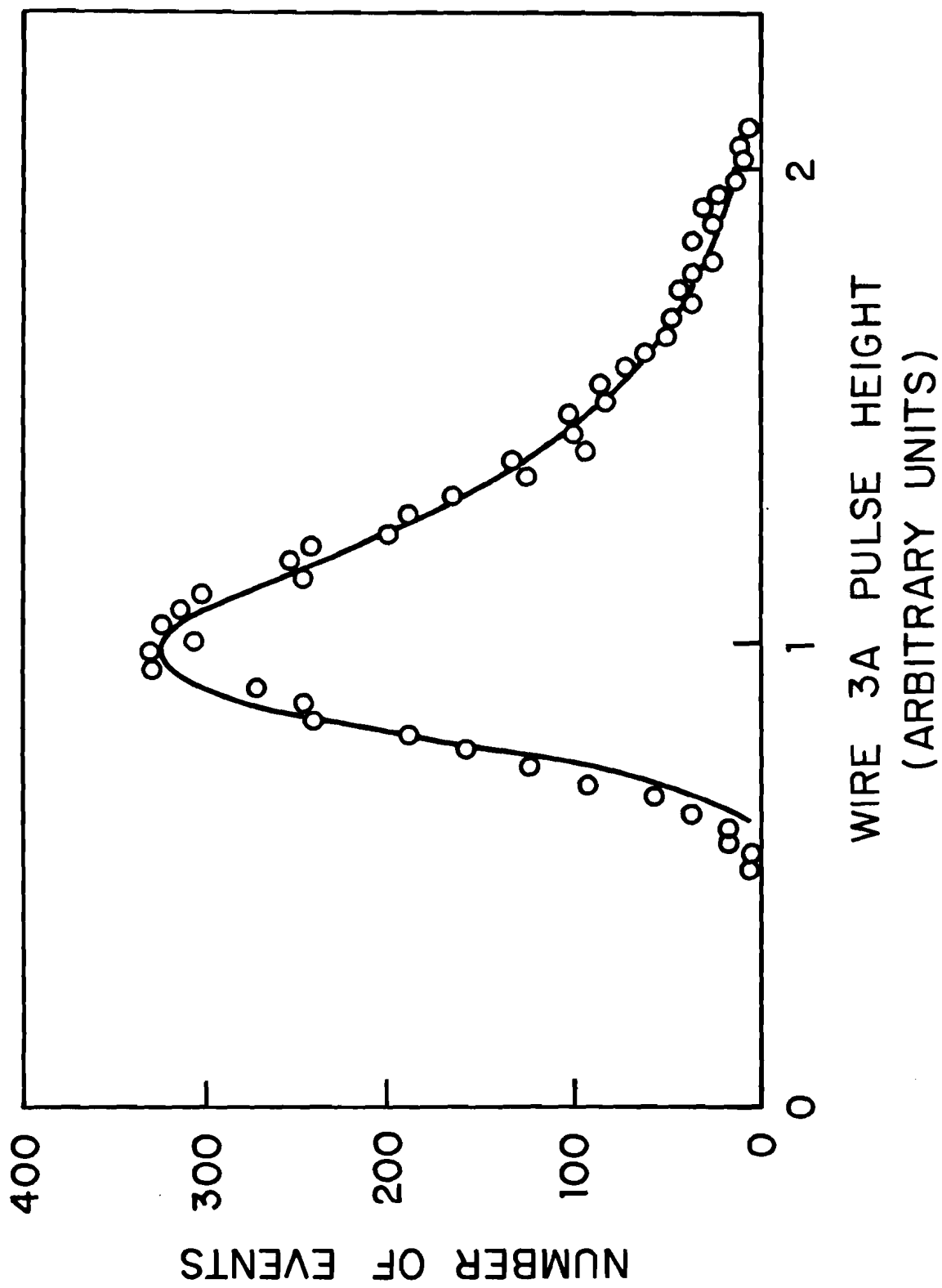


FIGURE 18

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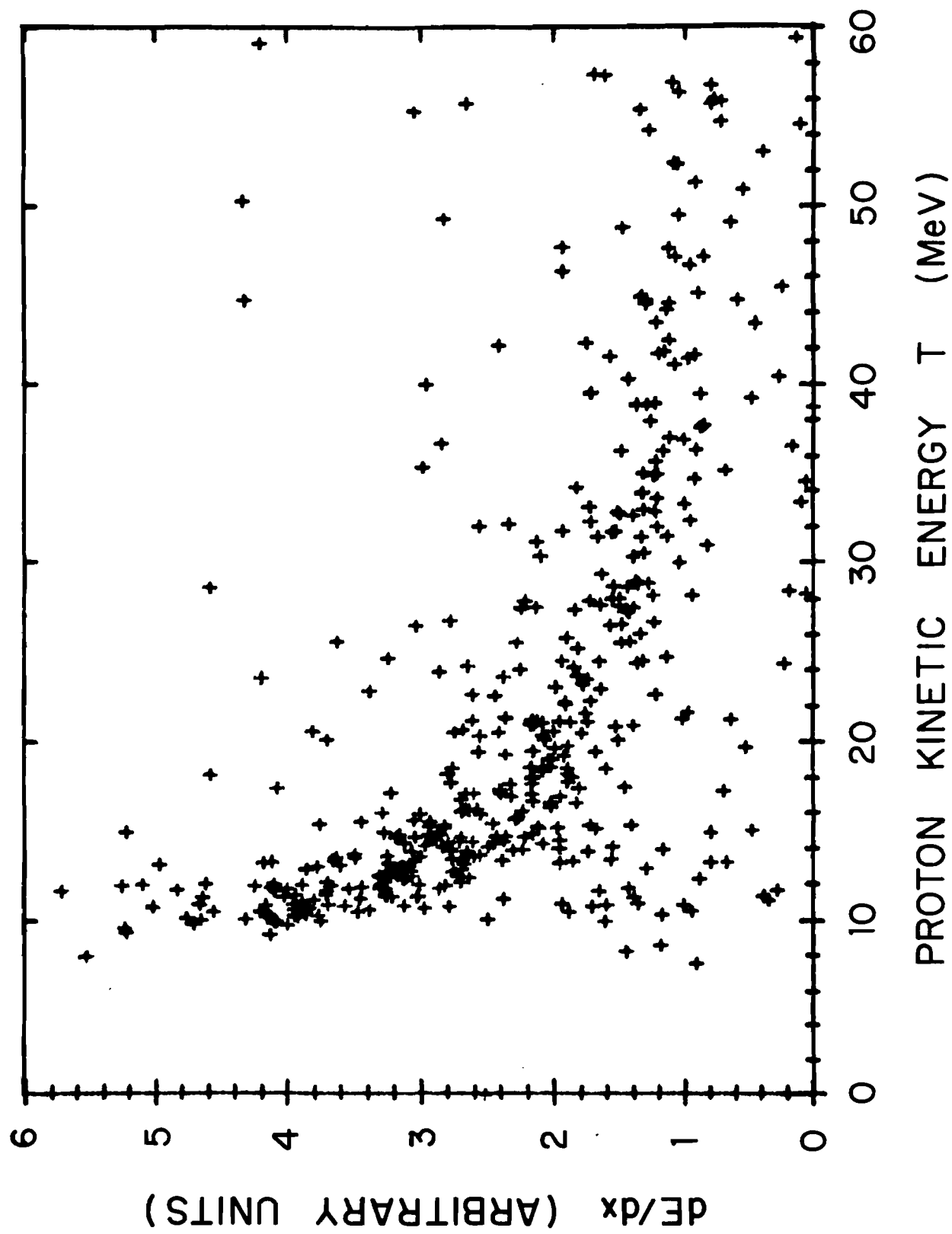


FIGURE 19

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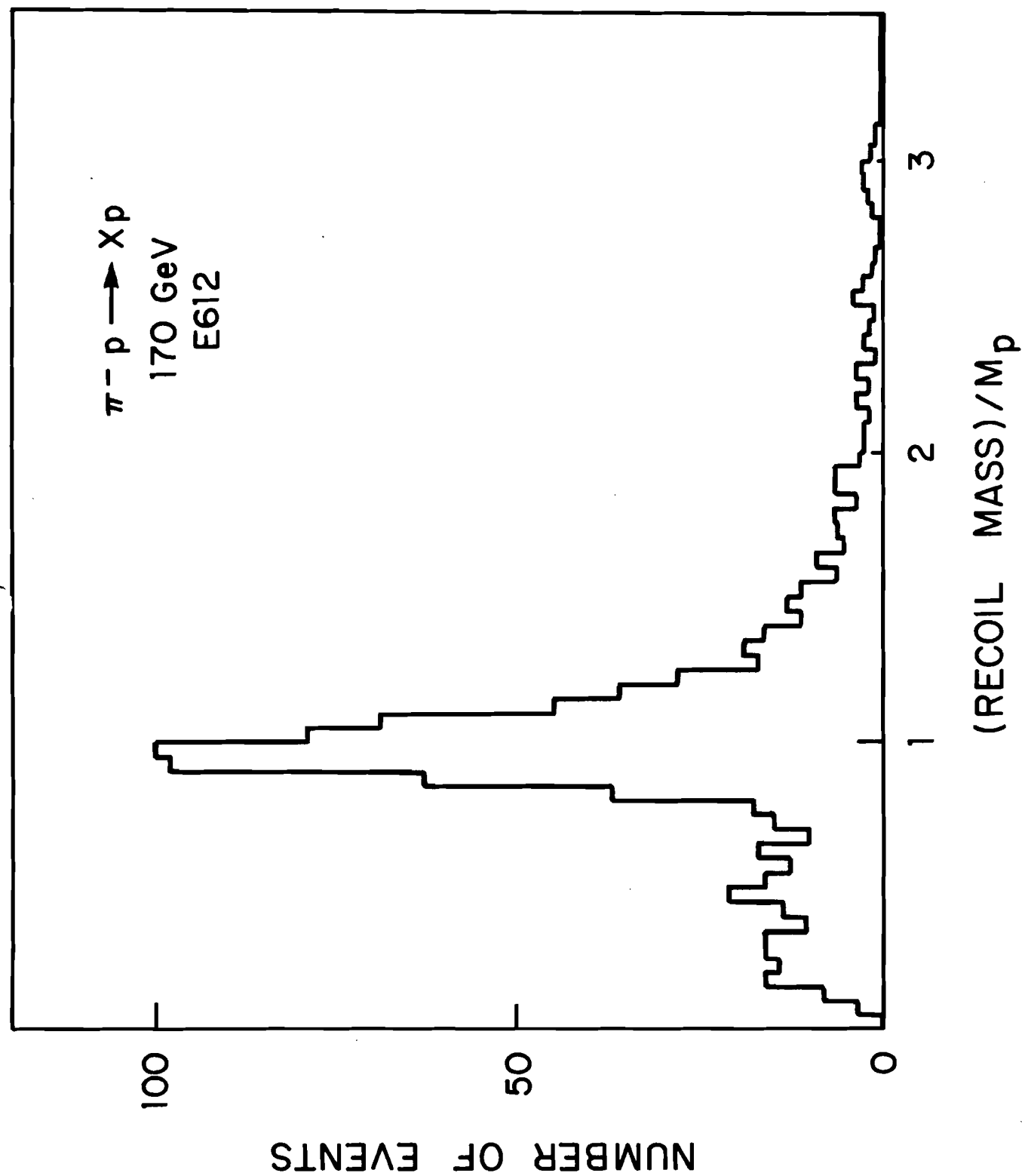


FIGURE 20

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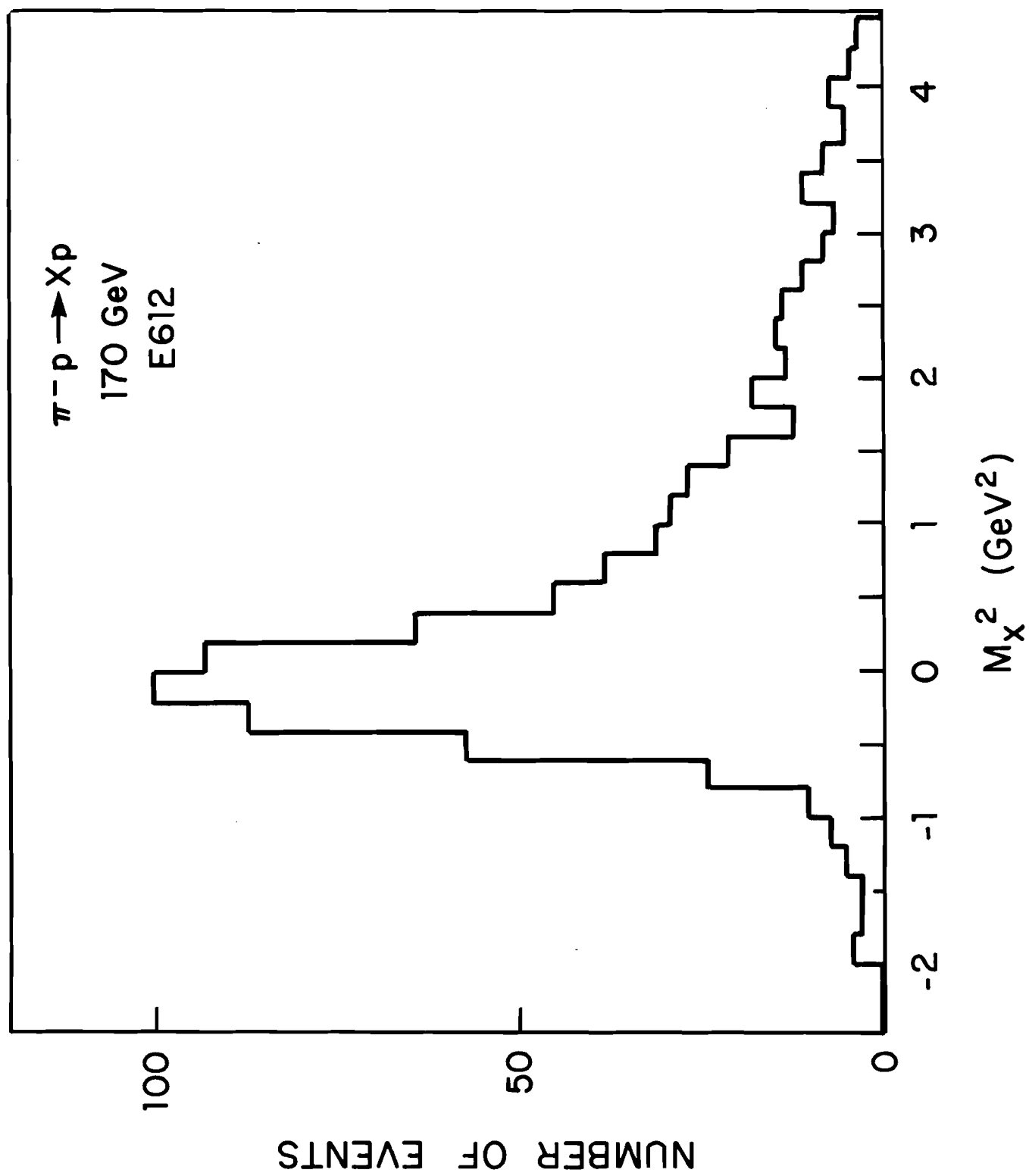


FIGURE 21

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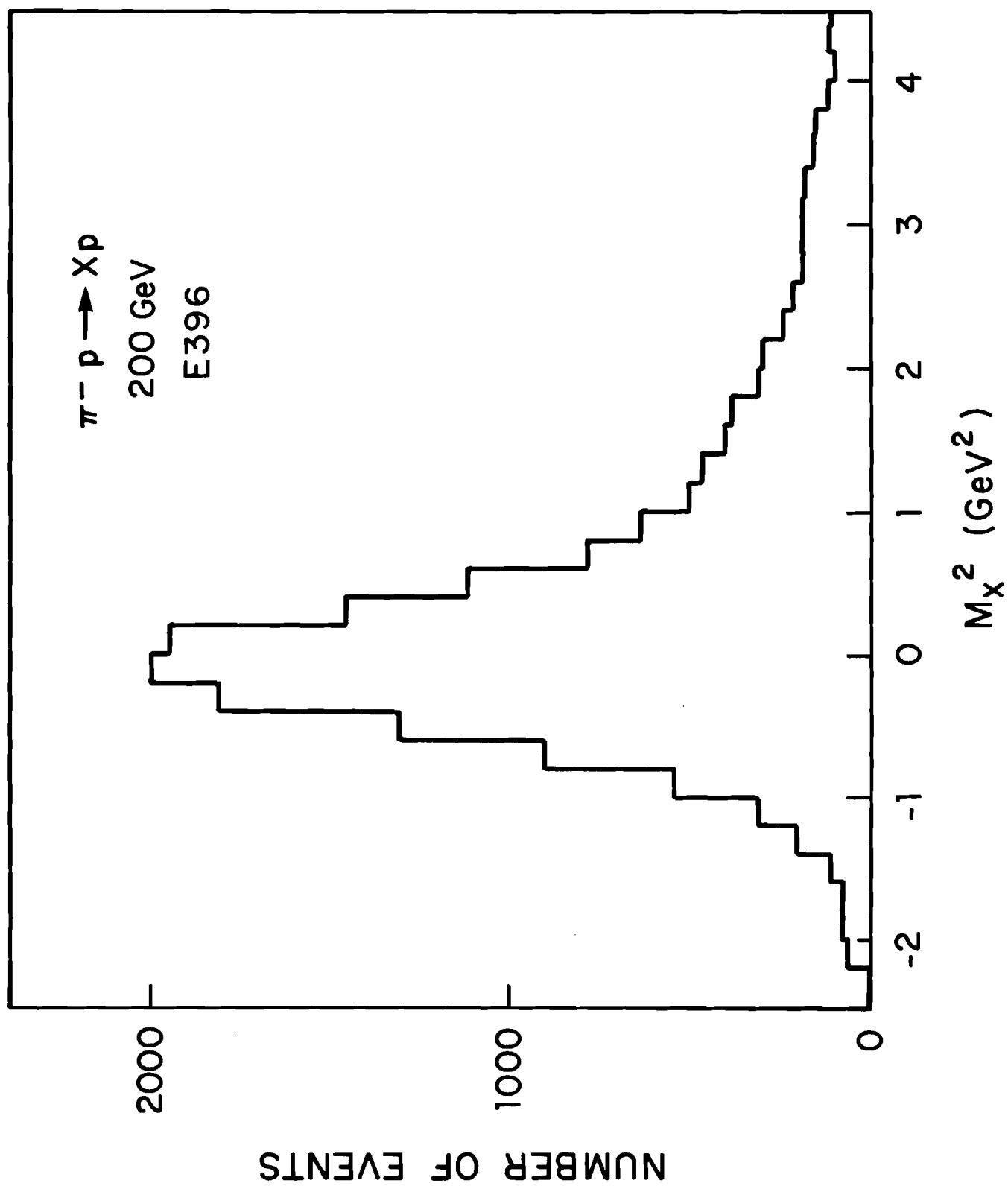


FIGURE 22

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