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RELATIVISTIC ELECTRON BEAM PROPAGATION IN NEUTRAL GASES: PINCHED BEAM GENERATION AND TRANSPORT

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Abstract

Relativistic electron beams with electron energies of about 350 KeV and $0.5 \leq \nu/\gamma \leq 3.5$ have been generated and drifted through a 1 meter long, 5 cm diameter drift tube. Pinching of the beam has been observed in both the diode and in the drift tube. Diode pinching occurs for a variety of cathode sizes when ν/γ exceeds a value of about 1.2 and is present in the drift tube for air pressures of less than 1 Torr. The propagating beam is grossly stable for pressures in the range 0.5 to 1.0 Torr. The pinching phenomenon has been explored for a number of different cathode sizes and types and for two thicknesses of anode foil to vary beam "temperature". The phenomena observed are described in terms of the neutralization development, diode pinch times and field energy requirements. A brief account is also given of the operation of a short dielectric rod cathode for the production of millimeter diameter beams.

1. Introduction

The generation and transport of high-current relativistic electron beams has been reported by a number of groups[1-5]. Recently the possibility of using intense beams for target plasma fusion studies has activated interest in the production[6,7] and transport[8,9] of high fluence beams. We report in this article on a study of the generation and transport of small diameter beams. This study is restricted to the case of beam transport in low pressure air. Earlier studies in other gases[5] have already indicated the scaling properties as the filling gas is changed.

Phenomenologically we note that small diameter beams are consistently produced in diodes using either plasma or aquadag cathodes when the injection value of ν/γ exceeds a critical value of about 1.2. This "pinching" process is only weakly dependent on the size of the cathode for the range of cathode sizes utilized. The propagation of this small diameter beam in the drift space is a function of the beam size and the ambient gas pressure. These parameters enter into the problem, apart from stability considerations, in the time taken to build up a highly conducting channel for efficient magnetic and electrostatic neutralization of the beam. Even in the optimum conditions for the transport of such beams there exists a net beam - plasma current of several kiloamperes. A condition for the development of such a channel is that the field energy needed for propagation has sufficient time to develop. We discuss in the following sections some of these criteria and their impact on beam propagation in a "pinched" mode. Experimental data supporting these arguments is presented in Section 3.

Self-pinching beams, as described above, do not present an optimum approach to the generation of small cross section beams. We present in Section 4 some results relating to the use of small dielectric rod cathodes for the generation of high fluence beams and indicate some of the limitations of these systems. Similar diode configurations have been reported in the literature by other workers[6, 7].

2. Models of Beam and Plasma Development

2.1 Diode Pinching

These processes have been discussed in some detail elsewhere[10, 11] and will only be outlined in this article. The development of a diode pinch depends on the aspect ratio of the diode utilized. Generally diodes have an anode-cathode separation d which is relatively small compared to the electrode radius r. In such geometries the anode and cathode plates tend to short out any radial electric fields, consequently the dominant radial force on the beam electrons is the v x B force on the particles. A criterion for the development of a pinch is that the electron orbit is radially compressed in a length comparable to the diode spacing. This leads to a critical current for diode pinching I_c such that

$$\frac{I_c}{I_A} \gtrsim \frac{r}{2d} \qquad (1)$$

where I_A is the Alfuen-Lawson critical current and is given by

$$I_A = 17,000\beta\gamma \qquad (2)$$

where $\beta = v/c$ and $\gamma = 1\sqrt{1-\beta^2}$. Experimentally, we observe, in the cases under consideration that Equation 1 does not present a good account of the critical current for pinching in the diode. We do, however, observe that a critical current does exist for pinching to occur. This is when

$$\frac{I_c}{I_A} = \frac{\nu}{\gamma} \sim 1.2 \; . \qquad (3)$$

Based on a linear rise of current with time we then define a diode pinch time τ_D as the time taken for the beam current to reach a value of 1.2 I_A. τ_D has a magnitude ranging from 50 nsec to 7 nsec as the average value of ν/γ at injection varies from 1.2 to 3.6. It is not completely clear at this time that diode pinching is not a result of a cathode "hot spot." The evidence given by the critical current for the pinch is, however, strongly suggestive of a pinch type process.

2.2 Ionization and Neutralization Time Scales

Putnam and Creedon have developed the basic concepts of the ionization development in a neutral gas. Initially ionization develops at a rate determined by the collisions between primary electrons and gas atoms. The plasma density n_p is then given as a function of time by

$$n_p = \int_0^t n_A \, n_b \, \sigma v_b \, dt \tag{4}$$

The first time scale relevant in the problem is the time taken to achieve a neutralization $f_E = 1 - \beta^2$ when radial force balance occurs for the primary electrons. Secondary electrons continue to be expelled by the electrostatic fields until $f_E = 1$. At this time the increasing primary current produces an axial electric field which drives secondary electrons back against the primary beam. Ionization occurs at a rate determined by the E/p for the system. Since the collision cross section for these secondary electrons is of the order of 10^2 greater than the primary ionization cross section and since this process leads to an avalanching it rapidly dominates over the primary ionization rate. Denoting the e folding time for plasma electron growth by this process by ν we find that the plasma density as a function of time is given by

$$\frac{dn_p}{dt} = \nu \, n_p + n_b n_A \, \sigma v_b \tag{5}$$

The quantity ν is taken typically from the experimental data of Felsenthal and Proud.[13] The process as described has no cutoff and as such breakdown times are somewhat arbitrary. Physically the process is limited by the development of return plasma currents and any associated ohmic voltage drops along the plasma channel. The current is then described macroscopically by the equation (for a fixed beam - plasma geometry)

$$L_B \frac{dI_B}{dt} = L_p \frac{dI_p}{dt} + I_p R_p \tag{6}$$

where the subscripts B and p refer to the beam and the plasma produced by the beam respectively. At low pressures $\gtrsim 1$ Torr the channel conductivity is high and the magnetic field and net currents are frozen at the value determined by the breakdown time. Consequently the net current rises to some value $\sim(d\, I_B / dt)\ \tau_B$ and thereafter remains frozen at this value decaying only on the long time scale $(L_p - L_B)/R$. At pressures significantly greater than 1 Torr the plasma electron - neutral momentum transfer limits the conductivity to values where the frozen field concept is no longer as good an approximation and the net beam - plasma current responds following the main trends exhibited by the primary current waveform.

Figure 1 shows the computed breakdown time, based on the scalar conductivity model, for various values of the induced electric field. The value $E = 1$ kV/cm typically corresponds to initial rates of current rise of about 10^{12} amps per second. The minimum in the breakdown time is associated with the maximum in the ionization cross section at about 200 volts. The ionization frequency ν used in these calculations is based on the Felsenthal and Proud data. Similar curves can be readily computed based on the known cross sections. This is of some relevance, as it is not immediately obvious that the planar electrode - applied field geometry of Felsenthal and Proud yields identical results to those obtained in the induction fields of the experiment. It should be stressed that the results computed are, at best, a rough description of the processes involved since, for example the field will be a function of radial position within the tube dropping to zero at the walls. The fields utilized in these calculations are more appropriate to the vicinity of the tube axis. A point in favor of these results is the remarkably good agreement one obtains between the onset of current neutralization experimentally and the times computed for breakdown. The cutoff in ionization was estimated in the above calculations by requiring that the ohmic voltage drop due to the plasma return currents be a lot less than the induced voltage. The time computed depends logarithmically on the plasma density ($\sim 5 \times 10^{14}$) assumed at breakdown.

In spite of the good agreement obtained between this model and breakdown times observed there are certain unsatisfying aspects of the model. Principally, in these calculations the existence of the self-magnetic field of the beam is ignored. In what follows we outline an alternate mechanism which could lead to breakdown in a comparable time scale to that estimated earlier.

An induced axial electric field will interact with the self-magnetic field of the beam to produce drifts on the secondary plasma in the radial direction. The relative importance of these drifts compared to axial drifts is determined by the magnitude of the parameter $\omega_c\tau_m$, where ω_c is the local cyclotron frequency and τ_m the momentum transfer collision time. For electrons with energy of the order of a few eV this parameter has a value of about

$$\omega_c\tau_m \sim \frac{2 \times 10^{-3}B}{p} \tag{7}$$

where p is in Torr and B in gauss. Based on an average value of $\omega_c\tau_m$ over the drift tube diameter and on a net current of 5 kA which we observe at about 1 Torr pressure, we conclude that a rough dividing line between isotropic and anisotropic return current flow would be expected at about 1 Torr pressure ($\omega_c\tau_m \sim 1$).

We now obtain a very rough estimate of the ionization frequency for the low pressure anisotropic case. At low pressures where $\omega_c\tau_m \gg 1$ the current flow is almost orthogonal to the electric field. During the breakdown phase $\tau_n \leq \tau \leq \tau_B$, $\omega_c\tau_m$ exceeds unity over most of the tube cross section. For an axial return current the radial electric field has a magnitude

$$E_r \sim \omega_c\tau_m E_z \sim a\partial B/\partial t \tag{8}$$

where a is a characteristic length scale for changes in B. (This could typically be the tube radius or for high density, the collision-less skin depth might be a more appropriate parameter.) The plasma electrons then acquire a drift velocity E_r/B in the axial direction, in time $\sim\omega_{ce}^{-1}$. The drift energy of these electrons is insufficient to cause ionization directly. They can, however, acquire random energy U_r at a rate determined by their drift energy U_D and the momentum transfer collision frequency

$$\frac{dU_r}{dt} = 2\,\nu_m\,U_D \tag{9}$$

Setting $U_r = eV_{ion}$ we find a characteristic ionization frequency ν_{ion}

$$\nu_{ion} = \frac{m\,\nu_{mom}}{e\,\gamma_{ion}}\left(\frac{a}{\tau_{rise}}\right)^2 \tag{10}$$

where $\tau_{rise}^{-1} \sim \frac{1}{I}\frac{dI}{dt}$ has a value of between 10 and 20 nsec. The breakdown time computed as shown earlier is also plotted in Figure 1. At higher presures (~ 1 Torr) the breakdown occurs earlier in time and the higher value of τ_{rise} is more appropriate. At low pressures τ_{rise} is smaller.

It is clear that one cannot distinguish between any breakdown mechanisms on the basis of the time to breakdown estimated as above. These calculations are meant to illustrate that the breakdown time is usually smaller than the pinch time for most reasonable estimates of parameters.

Since it is not possible on the basis of a measurement of breakdown times to assess the relative importance of these breakdown models (with a particle simulation this may be possible) it is relevant to ask if there are any distinguishing characteristics of these models which can be recognized. It is easiest to deal with this situation by examining the tensor conductivity model. An electron initially formed at rest in a crossed electric E_r and E_z, and magnetic field B_θ will be accelerated to velocity E/B in a time of the order of the reciprocal of the Larmor frequency. It does not, however, immediately acquire this velocity, but oscillates about this velocity with the local cyclotron frequency. The electrons finally acquire a steady drift velocity of E/B as these oscillations decay with a time scale ν_m^{-1}. The local cyclotron frequency is of the order of a few gigahertz and experimentally monitored radiation has been observed in X band having the correct duration, scaling with pressure, and ambient gas.[4] The radiation monitored would require emission at low harmonics. No observations have been made close to the fundamental frequencies. This observation and the rapid transition in plasma characteristics at pressures close to the transition $\omega_c\tau_m \sim 1$ lend some credence to the drift model at low pressures.

2.3 Field Energy Requirements

The presence of highly compressed electron beams leads to an additional constraint for beam transport, namely the provision of the required field energy. We examine this using two highly simplified models:

(a) The beam is compressed radially and the compression rate is limited by the rate of supply of energy.

(b) The beam is generated in compressed form and propagation is limited by the field energy requirements.

We assume in both cases that the beam is electrostatically neutralized and that some magnetic neutralization exists such that a net beam current I_N flows with a driving source I_B of beam electrons at energy V_B.

The field energy per unit length of beam is then

$$W_F = \frac{\mu_o}{2\pi}\left[\frac{1}{2} + \ln\frac{b}{a}\right] I_N^2 \tag{11}$$

where b is the tube radius and a the beam radius. On radial compression the change in stored field energy has to be supplied by the beam. The time taken to provide this energy τ_F is

$$\tau_F = \frac{K\mu_o\, I_N^2 \, \ln b/a}{2\pi\, V_B\, I_B} \tag{12}$$

where K is a constant taking into account that the beam current varies in time and that only a fraction of the beam energy goes to the magnetic field.

In the second case we can also compute the time taken τ_p for a beam to propagate a given distance, say 1 m, such that the beam can provide the needed field energy. Apart from a small additional term representing the self inductance of the beam we find $\tau_F = \tau_p$.

Equation 12 may be put in the more useful form

$$\tau_F = \tau_p = \frac{K\ 2(1-f_m)^2 \ln \frac{b}{a}}{c} \sqrt{\frac{\gamma + 1}{\gamma - 1}}\ \frac{I_B}{I_A} \qquad (13)$$

where f_m is the magnetic neutralization present and I_A is the Alfven Limiting Current.

We now present in the following sections an account of the beam characteristics and utilize the concepts presented above to help elucidate the mechanisms involved.

3. Experimental Results

Relativistic Electron Beams with energies in the range 250 to 400 KeV and $\nu/\gamma \leq 3 \cdot 6$ have been generated using a Mylar transmission line and propagated in 5 cm. diameter drift tube. Observations have been made using calorimetric and photographic techniques of the beam energy transport and behaviour. Rogowski loops have been used to measure the net beam-plasma current and radiographs and x-ray telescopes used to measure the spatial and time history of the beams. These studies have been conducted in both the diode and at the end of a 1 meter long drift tube.

3.1 Diode Pinching

X-ray pinhole cameras have been used to examine the occurence of a diode pinch. Figure 2 shows schematically the conditions under which a well defined pinch (to a diameter of about 0.8 cm) was observed. Pinching developed with both plasma and aquadag cathodes when ν/γ exceeded a value of about 1.2. Based on this critical value of ν/γ we estimate a time to pinch as a function of the mean value of ν/γ during the current pulse. This time is shown in fig. 3. Below the value $\nu/\gamma=1.2$ no pinching was observed. In the usual operating range $0.5 \leq p \leq 2$ Torr and $\nu/\gamma \leq 2.8$, the time to pinch in the diode exceeds the breakdown time scale for ionization in the drift tube.

3.2 Propagating Beams

The observed characteristics of beam propagation can be summarized as follows.

a) Low Pressures < 0.25 Torr - Beam always pinched as it propagates along the drift tube. As ν/γ increases the beam becomes grossly unstable.

b) Intermediate Pressures $0.4 \lesssim p \lesssim 1.0$ Torr - Beam pinched and frequently surrounded by a luminous halo - The beam is grossly stable and has a diameter of about 8 mm compared to a typical cathode size of 2.5 cm.

c) High Pressures of $p > 1$ Torr - Beam expands to fill drift tube - no evidence of pinching.

We present in the following sections a quantitative account of the beam characteristics with particular attention paid to the pinch mode of propagation.

The pinching characteristics of beams propagating in neutral gases are summarized in Figure 4. In this figure the ordinate is a subjective assessment of the pinched beam propagation, where the number 2 represents a well defined pinched column to a diameter of about 0.8 cm. and 0 represents no evidence of a pinched beam. This data was obtained for a number of cathode sizes and gas pressures and is based on photographic observation. The photographs correlate well with x-ray pinhole camera studies of the fast electrons infringing on a target at the end of the drift-tube. The pinch process was most well developed at a pressure of about 0.75 Torr and for a one inch diameter cathode. Pinching was established once again when the mean value of ν/γ exceeded a value of 1.2. Similar trends are observed with the larger diameter cathodes. In these cases the pinch is no longer well defined as ν/γ becomes large. The upper two curves indicate that pinched beams are obtained when the pressure is sufficiently low and also for small diameter cathodes even when ν/γ is well below unity. For the low pressure case the stability of the beam is poor as ν/γ is increased and the beam is liable to a hosing instability.

Calorimetric studies of the efficiency of energy transfer are presented in figure 5 for three different size cathodes. All show the same gross characteristics -- namely about 100% efficiency in the pressure range 0.5 to 1 Torr and a fairly rapid fall off on either side of this pressure window. On the low pressure side the beam is pinched and the large shot to shot variations are due to the erratic nature of the beam hosing. The drop in efficiency at higher pressures has its onset with the loss of the pinched column. In this pressure range the beam expands to fill the tube. The loss in energy is in part associated with the larger values of plasma resistivity (due to the increased electron-neutral collision frequency) and the associated energy loss in ohmic heating due to the return current and also due to increased wall losses. At the highest pressures examined the pinch nature of the beam reappears but energy losses are so large as to make this regime uninteresting from the point of high energy transfer efficiency.

In Figure 6 we show, for a one inch cathode system, measurements obtained from Rogowski coils of the net beam plasma current, the decay time of the plasma currents, and the efficiency of energy transfer. All of these curves exhibit a transition in behaviour as the gas pressure is increased above 1 Torr, ie., as the beam undergoes the transition from its pinch mode of propagation to one where the beam fills the drift tube. A similar transition is observed at the same pressure when the beam "temperature" is higher. The higher temperature beam is produced through the use of a 1 mil aluminum foil as anode instead of the alumized mylar foil. At the beam energies utilized the mean scattering angles in the two foils are approximately 22° and 6° respectively. Measurements of the net-current and energy transfer through the 1 meter tube are presented in Figures 7 and 8 for the two cases indicated above. Qualitatively we also observe that the beam pinch is less well defined with the higher temperature beam and has a larger diameter. From these observations we also conclude that the "temperature" of the beam is changed sustantially in the pinch mode as we change the anode foil thickness. Hence the mean angle of the electrons for the thin foil case must be less than the 20° scatter introduced by the 1 mil aluminum foil and hence the pinching process does not increase the beam temperature by an amount proportional to the final beam size compared to the cathode diameter. In both cases and over the pressure range examined it is possible to calculate the net current waveform and obtain good agreement with the observed waveform. The assumption made is that the beam-plasma current follows the primary current up to the time of breakdown and then is described by the circuit equation. Similar calculations have been reported by Jonas et al.(1)

Measurements have also been made using an x-ray scintillator photo diode of the pinched beam impinging on a target at the end of the one meter drift tube. A rapid increase in the x-ray yield is observed when the pinched beam hits the target (the telescope views a small area (approximately 1 cm^2) at the end of the tube). The time taken to this rapid increase in signal correlates well with the time taken for the pinch to form in the diode.

3.3 Discussion of Results

As indicated earlier the diode pinch time can either exceed ($p \lesssim 0.25$ Torr or $p \gtrsim 10$ Torr) or be less than the time taken for breakdown in the drift tube. We examine these two conditions separately.

a) Diode Pinch Time is less than the Breakdown time. In this case ionization develops in the channel but the avalanching is not complete by the time the beam pinch is initiated. In the limiting case of low pressures where electrostatic neutralization still occurs but the magnetic neutralization is small the presence of the pinch requires the development of a substantial investment in field energy. This must come from the beam injection. Using equation 13 we find that at low ν/γ this investment in field energy can be provided rapidly enough to allow the pinch to propagate but that at higher ν/γ this requirement is prohibitive. This mechanism provides an explanation for the gross instability of the beam low pressure and higher ν/γ.

b) Diode Pinch Time Exceeds the Breakdown Time. In this case, which covers most of the experiments performed, we find that the breakdown is complete prior to the diode pinch. In this regime there is no problem in providing both the electrostatic and magnetic neutralization needed for the pinched beam. Noting that the diffusion time is much greater than beam duration we conclude that if pinching occurs after breakdown then the return currents must redistribute themselves according to the new beam channel. Thus for a beam compression of three the self magnetic field at the edge of the pinched beam channel will only be about one third of its value prior to pinching and that the plasma electrons flow outside of the beam will be in the direction of the primary electrons. This reduction in the magnetic field at the beam edge and the observed beam diameters are consistent with mean values of $v_\perp/v_z$ of the order of 0.1 for the pressure range where stable pinch propagation is observed. It is also consistent with the increased beam diameter when the injection "temperature" is increased. A second consequence of the breakdown occuring prior to the pinch formation is that the net magnetic field distribution is unchanged within the drift tube. Consequently no problem arises in providing additional field energy for the pinched beam since no increase is needed. This accounts in part for the gross stability of the pinch in this pressure regime.

It should be noted that for the highest values of ν/γ utilized the pinch can occur in the diode in a time shorter than the breakdown time, hence we expect and observe a loss of a well defined stable pinch in this regime.

These explanations are all based on the relative time scales for pinching and breakdown. As already pointed out in Section 2, the breakdown time scale is not readily calculated with any precision and is also a function of the radial position within the drift tube peaking towards the center of the tube. For reasonable estimates of the parameter we conclude however that this transition should occur close to the observed parameters. It is probable though that the plasma formed does not fill the tube and is probably restricted to a region of about the same dimensions as the cathode.

It now remains to describe the transition from the pinch mode of propagation to the diffuse mode. This transition occurs at about 1 Torr pressure in air and scales with the ionization probability of the gas. This problem is complex and only a possible qualitative explanation will be proffered. A significant amount of evidence exists which is consistent with the anisotropic model of the breakdown for the low pressure cases. All calculations made to date, eg. Rostoker and Hammer [14] of the return current development have treated the beam dynamics self-consistently but have ignored the effects of the self magnetic field on the return plasma currents. Within the framework of the model present earlier of breakdown in the anisotropic case we must conclude that radial motion of the plasma electrons is largely prohibited by the self-magnetic field of the beam-plasma system. This situation is compared with that which is obtained for the case where the self-magnetic field effects are unimportant. For such a case, even if the breakdown is mainly in the vacinity of the tube axis diffusion of the plasma to the walls is readily possible. An empirical observation of beam transport processes indicates that the beam electrons preferentially flow through the region where the ionization exists. Any departure from this channel causes the development of strong electrostatic forces tending to drive the beam electrons back to the conducting channel. Based on the estimates made in Section 2 we find that the transition from the anisotropic to the isotropic regime occurs at about 1 Torr pressure. For the low pressure side of this transition plasma electron flow across the field lines is prohibited whereas at higher pressures the collision frequency is high enough that the motion of the plasma electrons radially is unimpeded by the magnetic field.

4. Dielectric Rod Cathodes

Obtaining a pinched beam by relying on the self pinch properties within the diode is not the most efficient way of obtaining small diameter beams. We have utilized small section dielectric or metalic rod cathodes for the production of a high fluence beam. The system used is similar to that employed by Bennett, et al. A schematic of the diode is shown in Figure 9. The rod is much shorter than that used by Bennett. Radiographs taken at the anode plane show beam diameters of about 1mm. These beams are liable to violent hosing and very small diameter drift tubes are needed to limit the field energy demands. In Figure 10 we show a plot of the impedance of the diode as a function of the gap spacing. The impedance drops to a relatively low value as needed for efficient beam generation. Calorimetric measurements made using a calorimeter with an axial plug to allow only electrons outside of the plug to be recorded on the calorimeter indicate that the beam energy is in fact carried within the channel recorded by the radiographs. Such beams may have application in beam-pellet heating experiments.

5. Conclusions

We have observed self pinching of electron beams in transport through neutral gases. The pinch has been shown to originate in the diode and the development of the stable pinch mode of propagation has been described in terms of the relative time scales for breakdown in the tube and pinching in the diode. A necessary criterion for pinch propagation is also obtained by considering field energy requirements. The transition from a pinched to a diffuse beam can be qualitatively related to the self-magnetic field effects on the plasma electrons. The above considerations point out some of the limitations for the transport of highly pinched beams such as those which can be obtained using small diameter dielectric or metalic rod cathodes.

6. Acknowledgement

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FIGURE CAPTIONS

Fig. 1 Breakdown Time Computed as a Function of the Gas Pressure

Fig. 2 Diode Pinch Development as a Function of ν/γ

Fig. 3 Diode Pinch Time as a Function of ν/γ

Fig. 4 a) Pinch Quality as a Function of ν/γ
b) Pinch Quality as a Function of Ambient Gas Pressure

Fig. 5 Energy Transport as a Function of Pressure for Various Cathodes

Fig. 6 Energy Transfer, Net Beam-plasma Current and Plasma Decay Times Versus Ambient Pressure

Fig. 7 Variation of the Net Beam-plasma Current with Pressure for Different Beam Temperatures

Fig. 8 Variation of Energy Transfer with Pressure for Different Beam Temperatures

Fig. 9 Schematic showing Assembly of Diode using Small-rod Cathode

Fig. 10 Diode Impedance for Rod Cathode Diodes as a Function of the Diode Spacing

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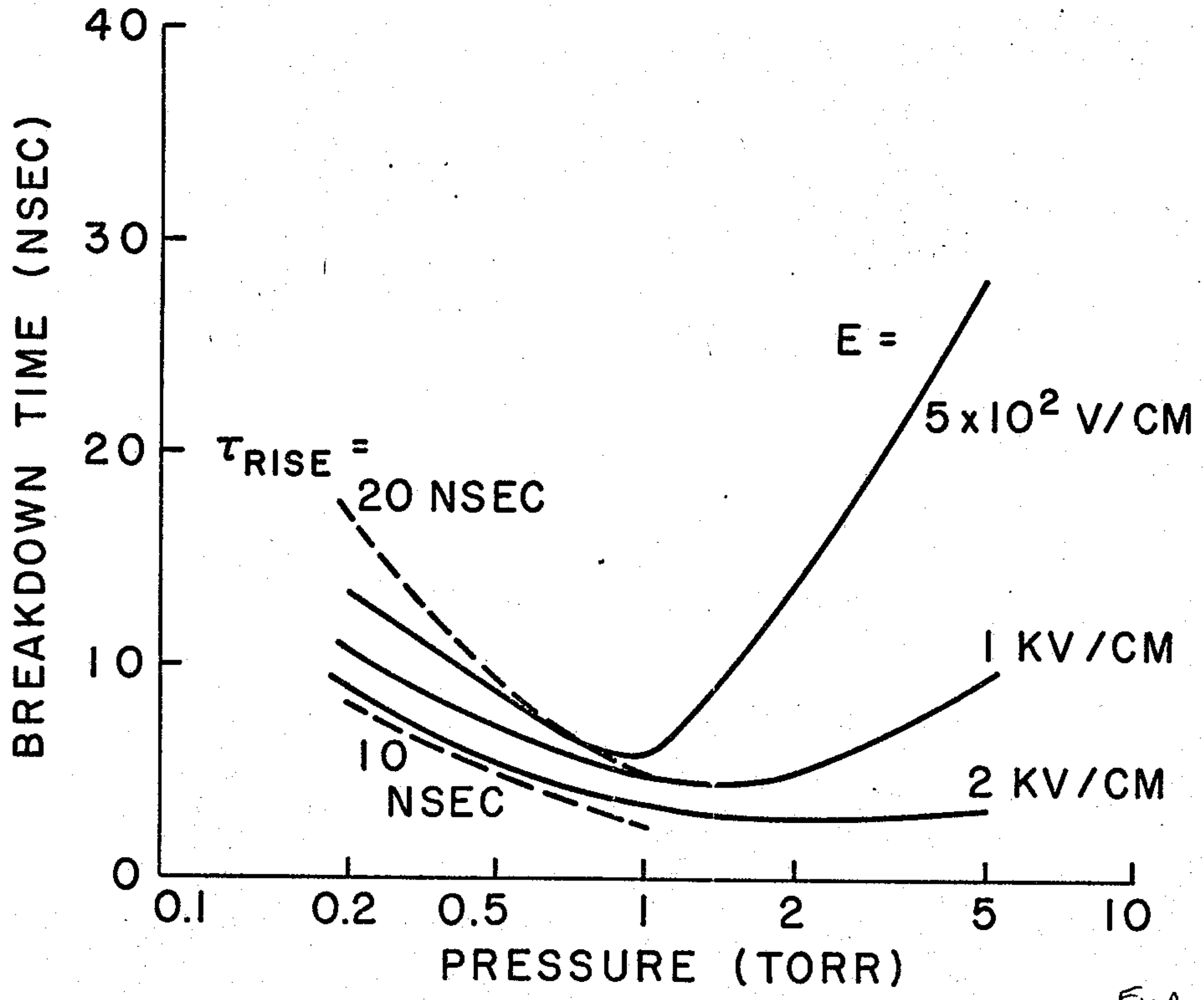

BREAKDOWN TIME (NSEC)
40
30
20
10
0
0.1
0.2
0.5
1
2
5
10
PRESSURE (TORR)
E =
5 x 10^2 V/CM
1 KV/CM
2 KV/CM
τ_{RISE} =
20 NSEC
10
NSEC

Fig 1

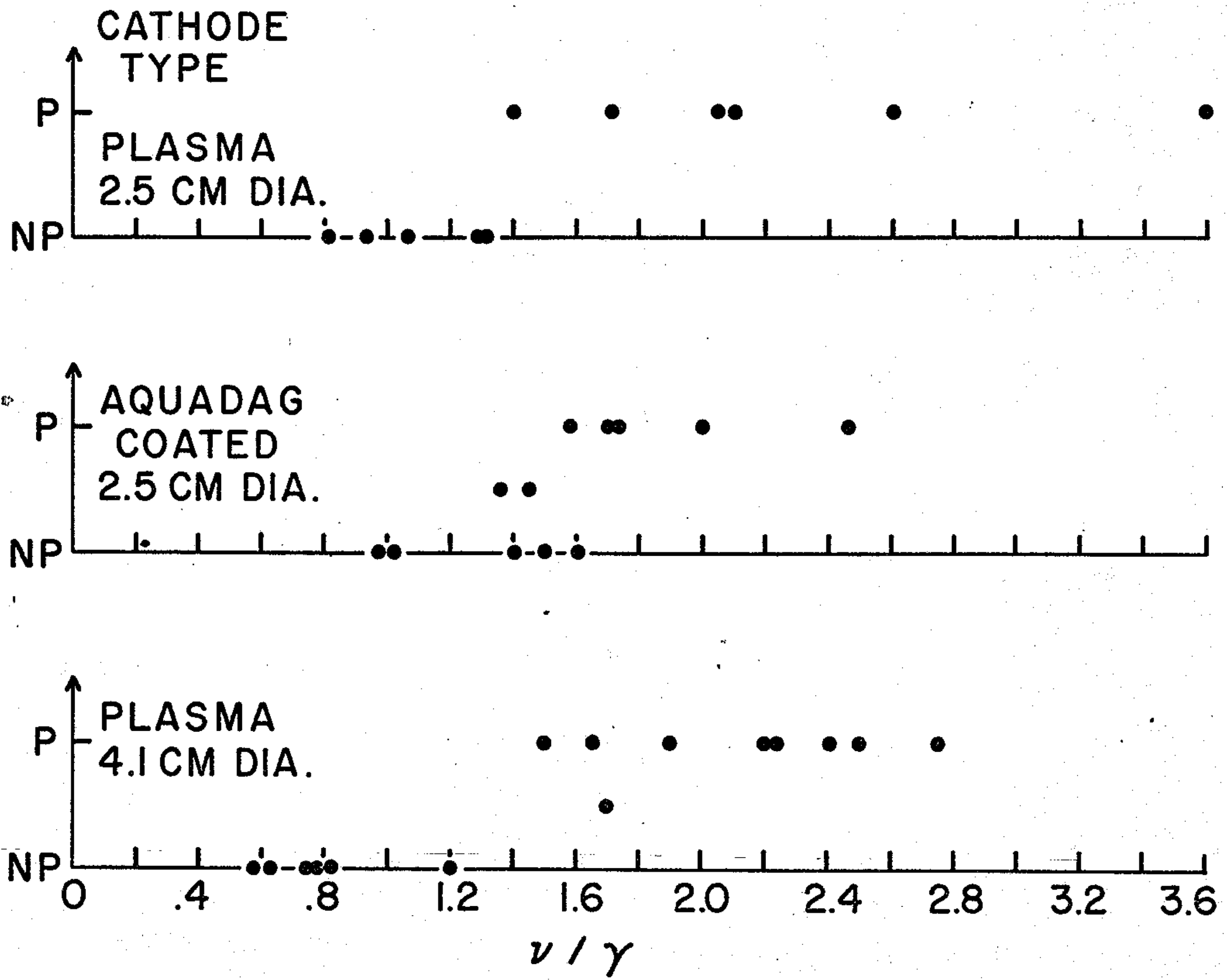

OCCURRENCE OF DIODE PINCH VS. ν/γ

Fig 2

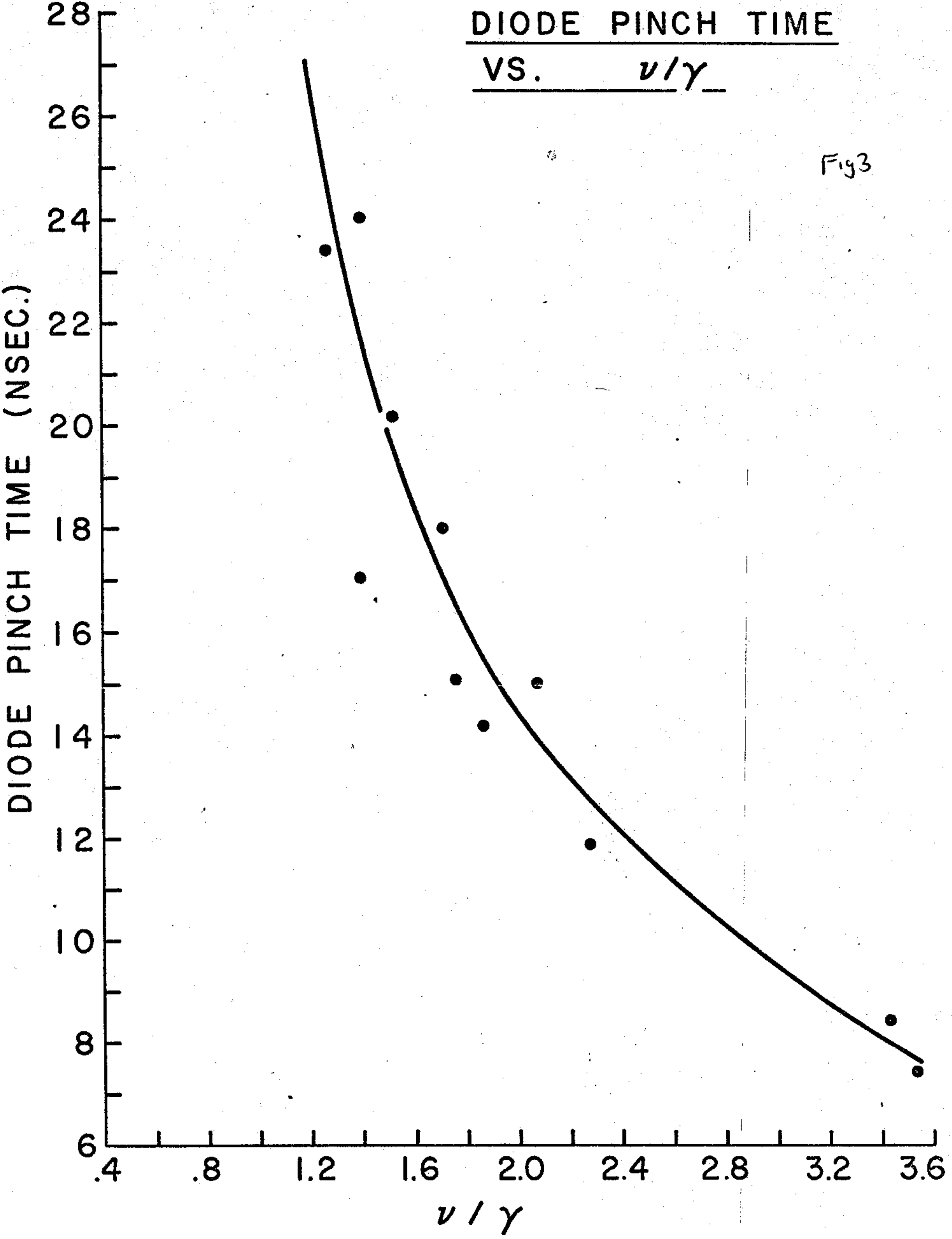

DIODE PINCH TIME
VS. ν/γ
DIODE PINCH TIME (NSEC.)
28
26
24
22
20
18
16
14
12
10
8
6
.4
.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
ν / γ

Fig3

I

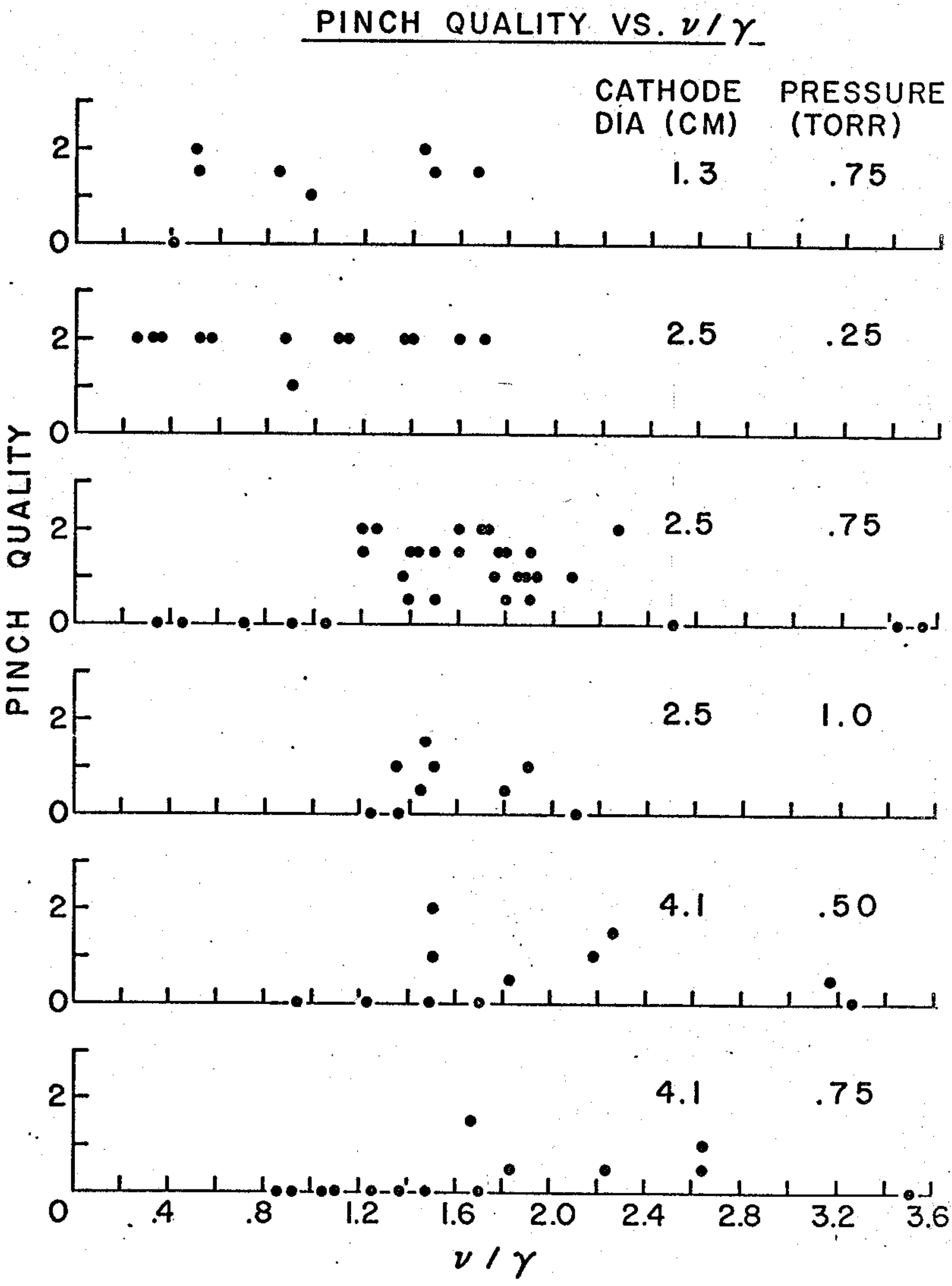

PINCH QUALITY VS. ν/γ
CATHODE DIA (CM)
PRESSURE (TORR)
1.3
.75
2.5
.25
2.5
.75
2.5
1.0
4.1
.50
4.1
.75
PINCH QUALITY
0
2
0
.4
.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
ν / γ

Fig 4a

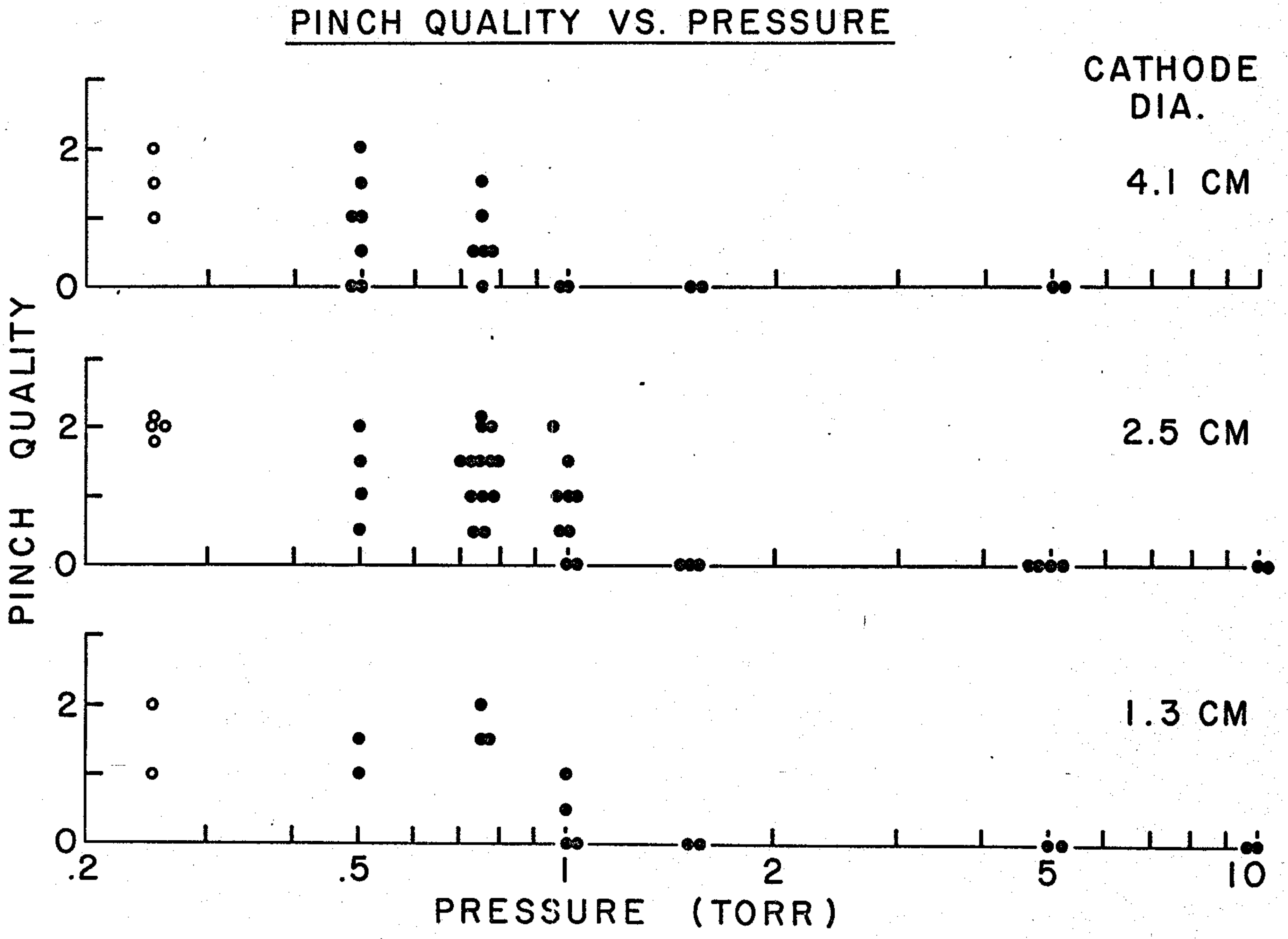

PINCH QUALITY VS. PRESSURE
CATHODE DIA.
4.1 CM
2.5 CM
1.3 CM
PINCH QUALITY
2
0
2
0
2
0
.2
.5
1
2
5
10
PRESSURE (TORR)

Fig 4b

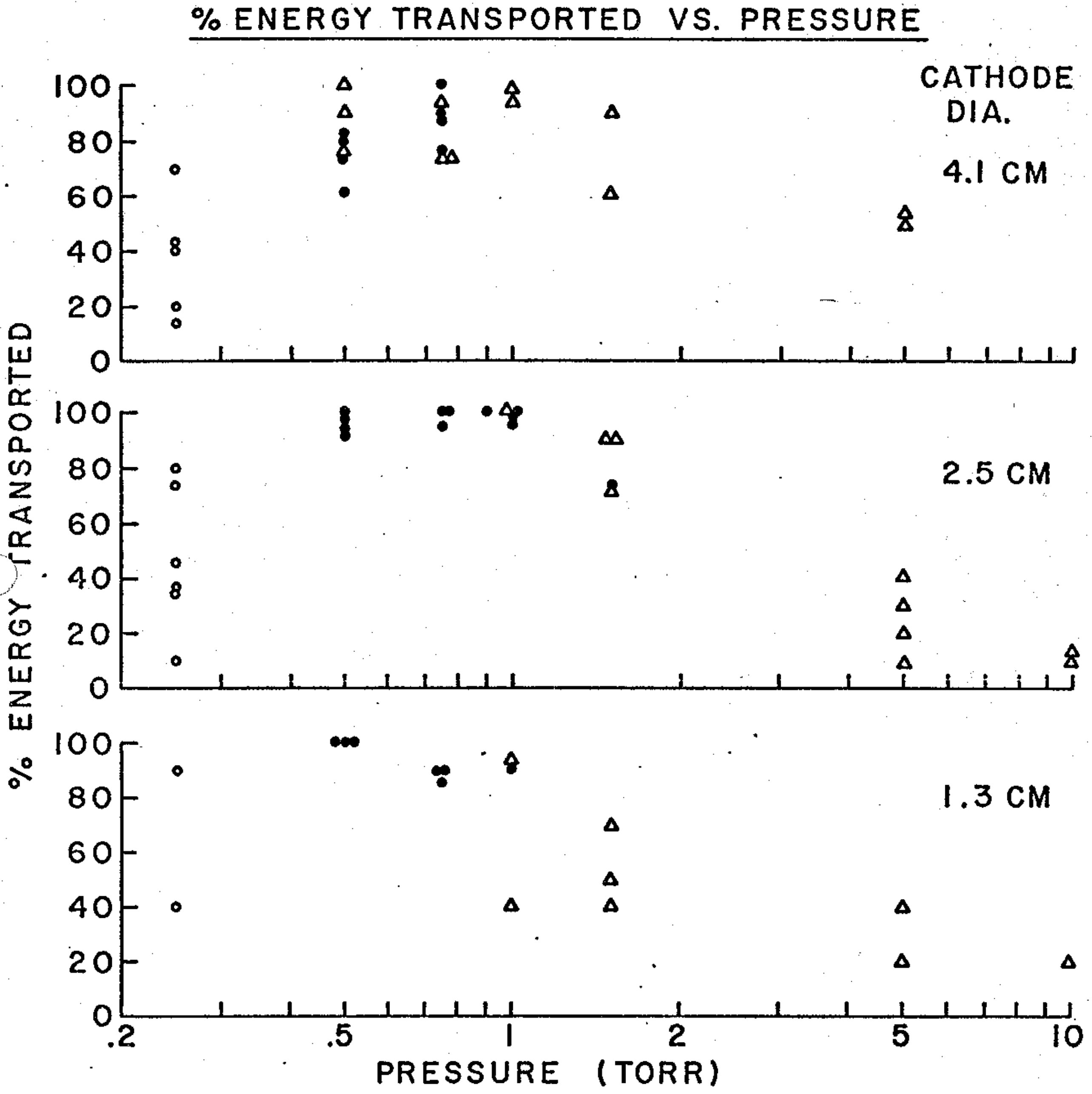

% ENERGY TRANSPORTED VS. PRESSURE
CATHODE DIA.
4.1 CM
2.5 CM
1.3 CM
% ENERGY TRANSPORTED
100
80
60
40
20
0
.2
.5
1
2
5
10
PRESSURE (TORR)

Fig 5

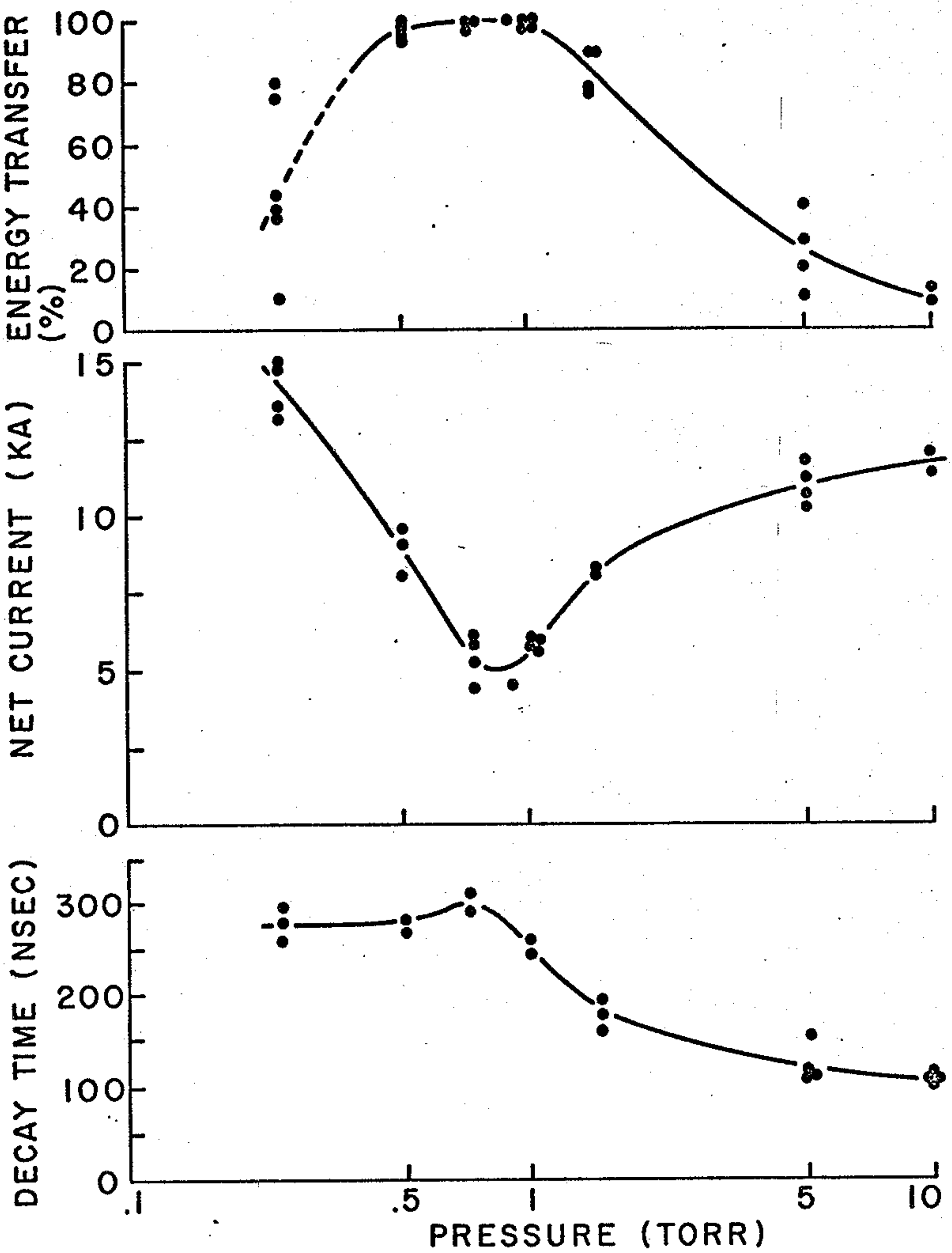

ENERGY TRANSFER (%)
100
80
60
40
20
0
NET CURRENT (KA)
15
10
5
0
DECAY TIME (NSEC)
300
200
100
0
.1
.5
1
5
10
PRESSURE (TORR)

Fig 6

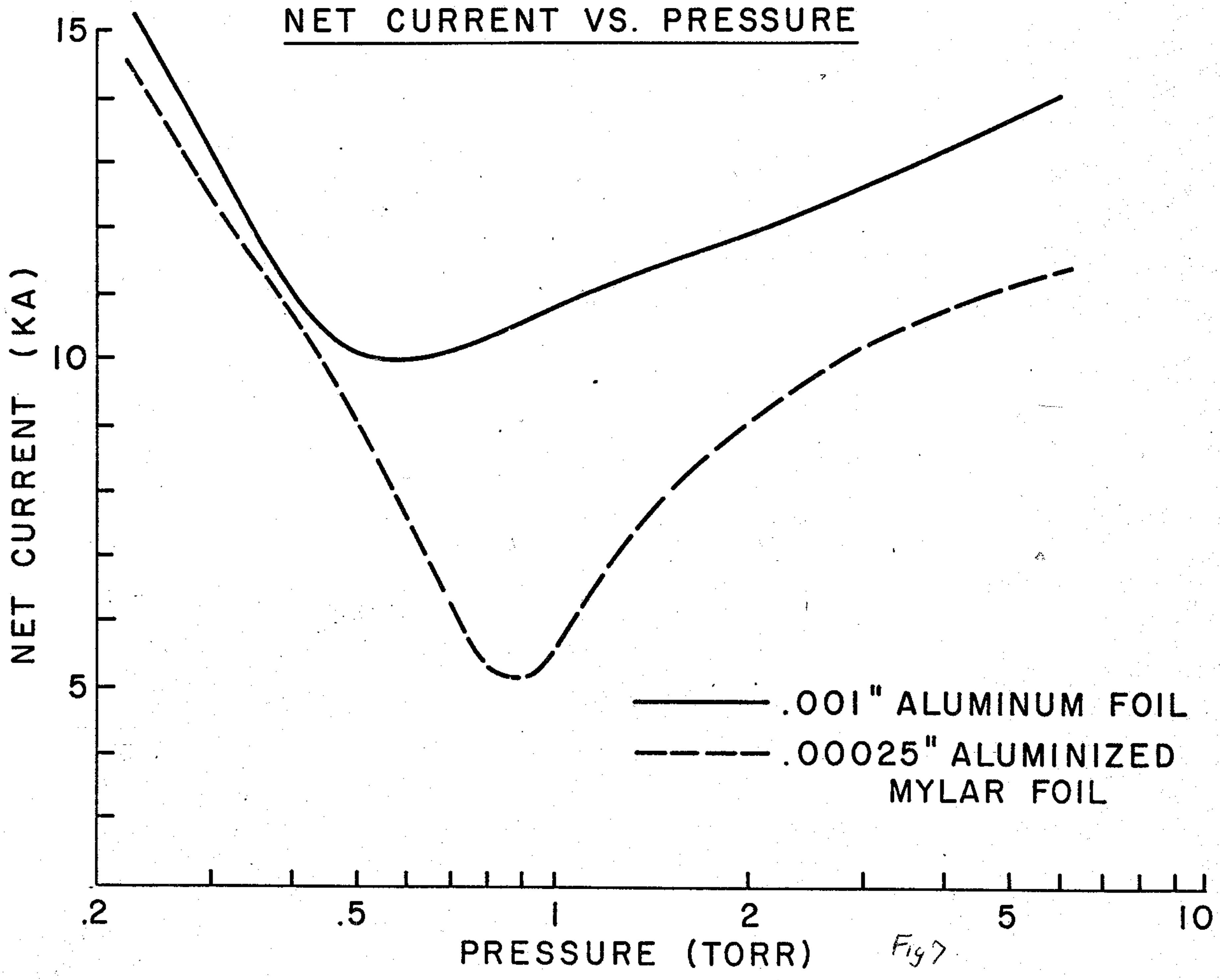

NET CURRENT VS. PRESSURE
NET CURRENT (KA)
15
10
5
PRESSURE (TORR)
.2
.5
1
2
5
10
.001" ALUMINUM FOIL
.00025" ALUMINIZED MYLAR FOIL

Fig 7

ENERGY TRANSPORT VS. PRESSURE

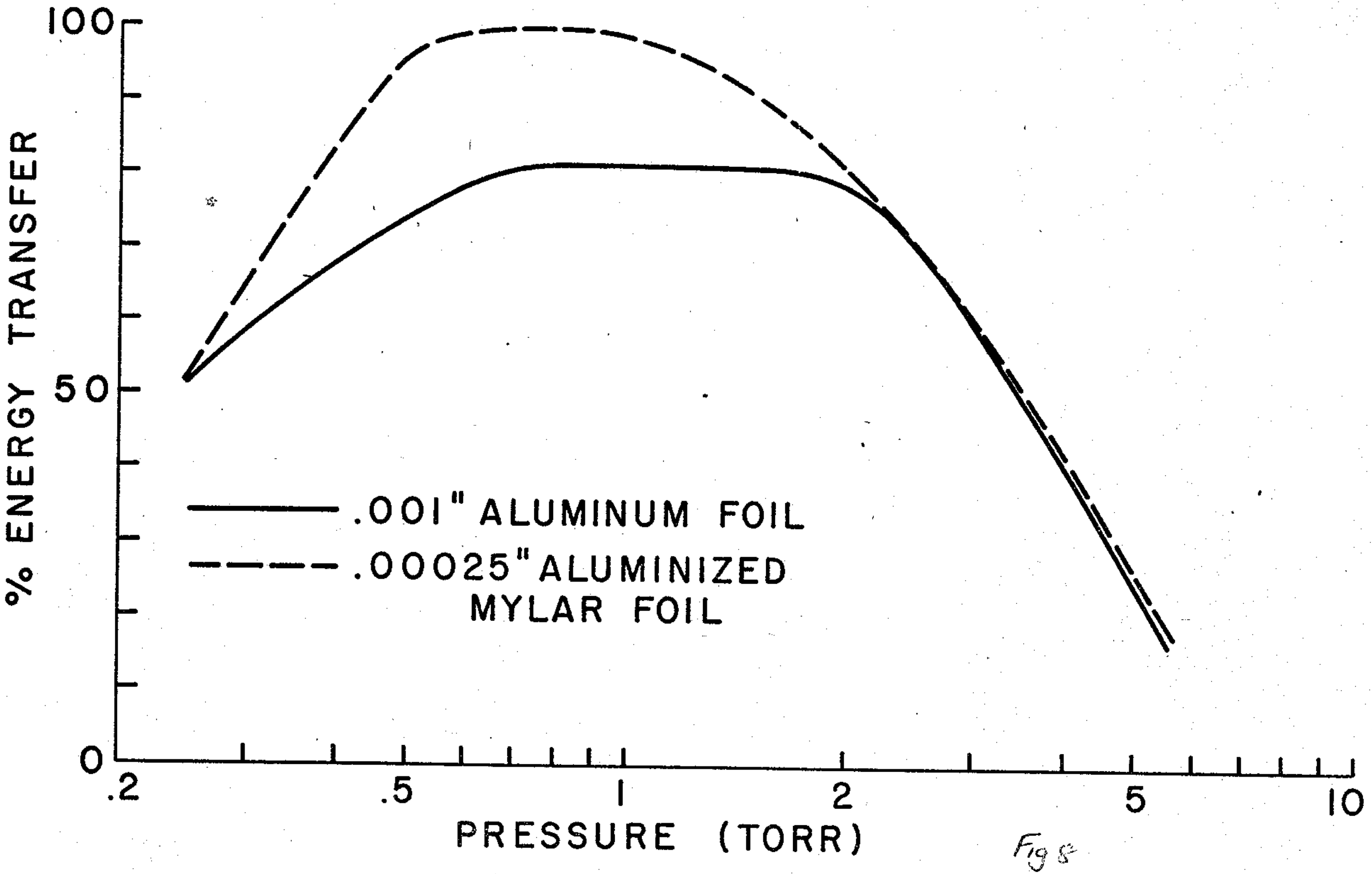
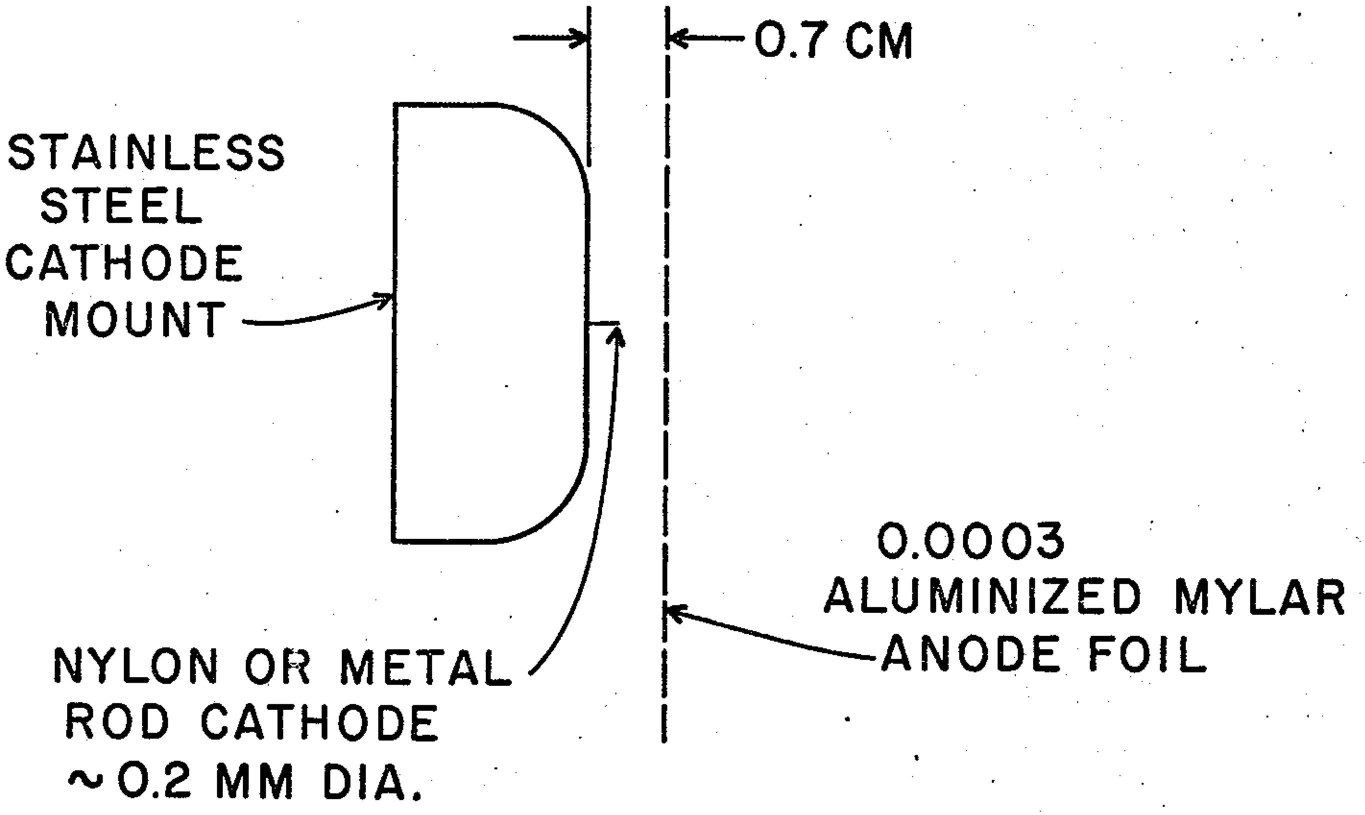


Fig 5



SCHEMATIC OF "ROD CATHODE" DIODE ASSEMBLY

Fig 9

H

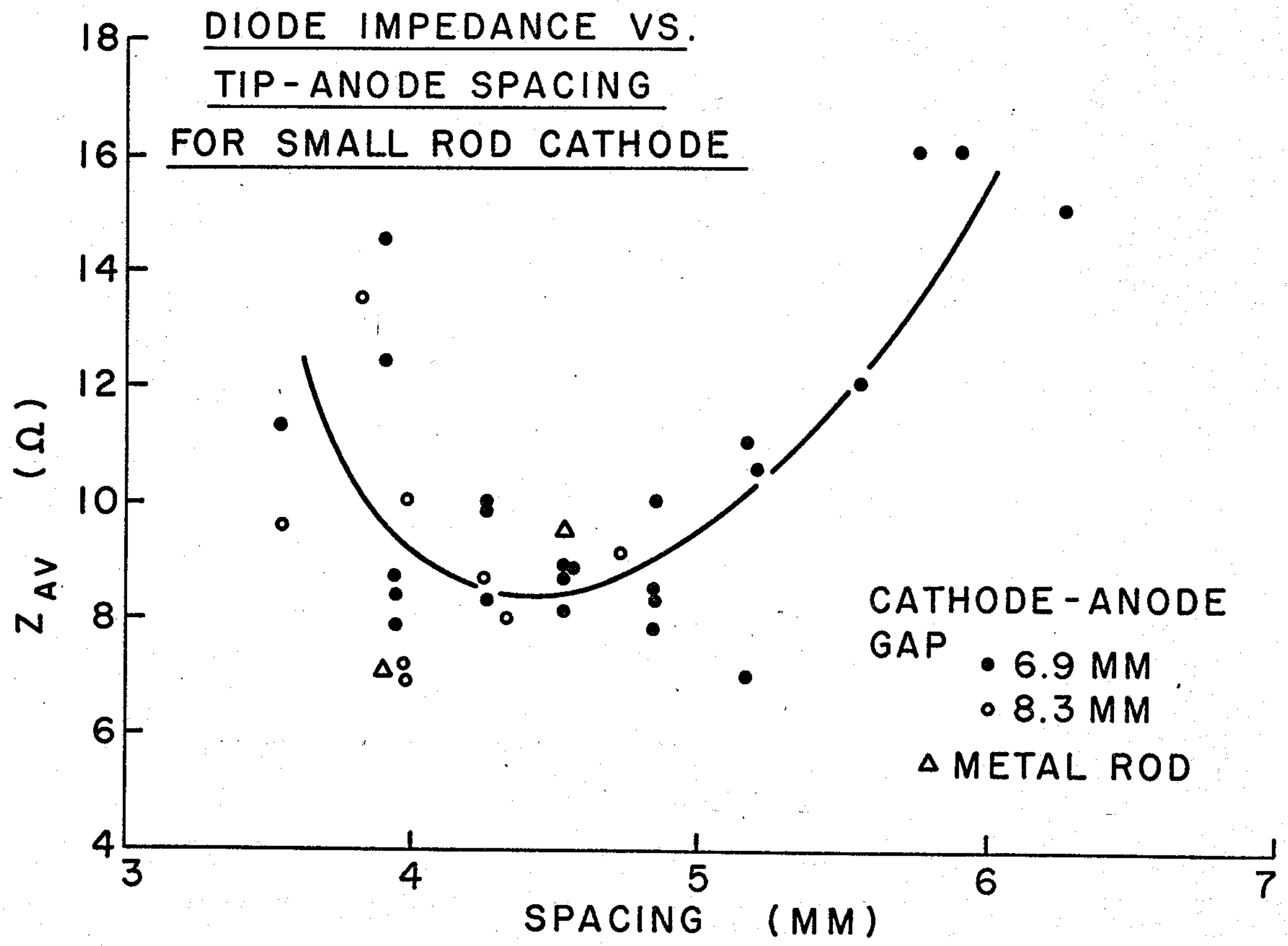

DIODE IMPEDANCE VS. TIP-ANODE SPACING FOR SMALL ROD CATHODE

Fig 10