PULSED MICROWAVE MEASUREMENTS IN GASES WITH A LOW DEGREE OF IONIZATION

by

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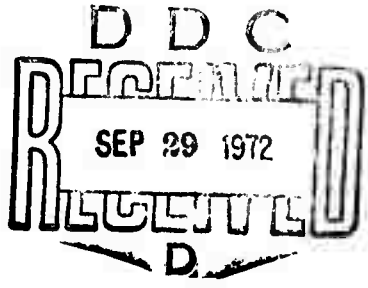

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ABSTRACT

This paper presents the results of experiments on microwave breakdown at an open end waveguide antenna in Air, Argon, Nitrogen, Carbon Dioxide and Methane at pressures of 0.3 and 30 Torr. The antenna was operated at 9.375 GHz under pulsed conditions at varying pulse rates. Very low degrees of preionization were obtained by adjusting to very slow pulse rates. The power needed to maintain the discharge was measured and from that the electric field strength was calculated. This is presented as a function of pressure for each gas at pulse rates ranging from 10 to 500 pulses per second. At low pulse rates, significantly higher power levels are needed to maintain the discharge. An interesting feature is the double minima observed at low pulse rates in the data for breakdown field strength as a function of pressure for Carbon Dioxide and Methane. The data was also used to calculate ionization frequency as a function of effective electric field for all five gases. Where possible, this data is compared with data reported by other investigators.

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I. INTRODUCTION

Microwave breakdown of gases has been investigated for many years by many researchers[1-12]. For the purpose of studying electrical breakdown characteristics of a gas, microwave discharge experiments have the advantage over the other discharge experiments of eliminating electrode influences on the discharge, thus simplifying the interpretations. MacDonald has covered most of the microwave work that was done before 1966 in his book (Ref. 1) with extensive references to others' work. The gases studied have mainly been Air, for its practical importance and the noble gases because they could be treated theoretically. Little work has been done on polyatomic gases.

Much of the experimental work was done with c.w. fields in which the microwave breakdown field strength depends only on four parameters: the ionization potential of the gas molecules, the mean free path of electrons in the gas which is inversely proportional to pressure, the diffusion length, which is governed by the dimension of the breakdown region, and finally, the frequency of the applied field. In pulsed fields, however, the pulse width and initial electron density are also factors. Since it is the free electron in a gas that will most readily absorb energy from an applied microwave field, it is important to have a few free electrons in the gas to start a discharge. Most previous investigators have resorted to radioactive sources to provide the low level free electron density needed to initiate a discharge[1,4,7]. Such experiments result in lower bound measurements of breakdown field strength.

In this paper, experiments on pulsed discharges in which the free electrons from the previous pulse serve as the source of initial free electrons are discussed. Pulse rates were varied to determine the maximum power levels applicable at very low pulse rates before the

onset of breakdown. Somewhat similar experiments in Helium were reported by Mentzoni and Donehoe[16]. The experiments reported here were conducted in Air, Argon, Nitrogen, Carbon Dioxide and Methane. These provided data which could be compared with other reported data and produced data which may be of value in designing spacecraft to operate on other planets. Some interesting and unexpected results are discussed.

II. BACKGROUND

The basic theory of microwave breakdown of gases is well-known and is discussed in many references (Refs. 1-6 among others). The theory is developed from the continuity equation for electrons in a small element of volume in the field. Consideration of the conditions of these experiments leads to a relatively simple expression for the continuity equations.

First, ionization caused by sources other than the action of the microwave field is neglected. This is a common assumption and usually good except in very hot gases such as occur in re-entry sheaths. Also, recombination of electrons and ions is neglected since it is proportional to the product of electron and ion densities. From the available data, this is seen to be very small prior to breakdown. A net ionization frequency, ν_{net}, is used since that is what can be determined experimentally. This is given by

$$\nu_{net} = \nu_i - \nu_a \qquad (1)$$

where ν_i and ν_a are the ionization and attachment frequencies per free electron, respectively. Finally, the diffusion term $\nabla^2(Dn)$ is approximated by $-(D/\Lambda^2)n$ where n is the free electron density, D is the diffusion coefficient for free electrons in the gas, and Λ is the characteristic diffusion length. This approximation assumes D is

spatially constant and there is only one mode of diffusion which decays in the characteristic distance Λ. With these assumptions, the continuity equation may be written as

$$\frac{\partial n}{\partial t} = (\nu_{net} - \frac{D}{\Lambda^2})n \qquad (2)$$

The further assumption is made that ν_{net}, D and Λ are constant in time.

In c.w. fields, breakdown is said to occur if the production rate exceeds the loss rate but in pulsed fields, it must exceed it by a sufficient amount to produce some critical level of electron density, n_b, during the pulse. Then, if there are n_o free electrons at the start of the pulse which is of width τ, Eq. (2) may be integrated to show that the condition needed to achieve breakdown in a pulsed microwave field is

$$\nu_{net} \geq \frac{D}{\Lambda^2} + \frac{1}{\tau} \ln \frac{n_b}{n_o} \qquad (3)$$

The net ionization frequency, ν_{net}, is a function of the applied field strength, its frequency, the gas in question, and its pressure. Experimentally, it is most often plotted as a function of effective electric field which is defined as the d.c. field, which would produce the equivalent energy transfer to the electrons. The effective electric field E_e is given by

$$E_e = E/[1 + (\frac{\omega}{\nu_m})^2]^{\frac{1}{2}} \qquad (4)$$

where E is the rms electric field strength

ω is the angular frequency of the applied field

ν_m is the electron collision frequency for momentum transfer

Then, the power gain by an electron in the field is just

$$P = \frac{e^2 E_e^2}{m \nu_m} \qquad (5)$$

where e and m are the electron charge and mass.

It is well-known that if an electron did not undergo collisions, it would gain no net energy from the microwave field because its velocity would always be exactly out of phase with the field. With collisions,

however, the average electron gains energy on each elastic collision despite the randomness of the process, because the energy gain is proportional to E^2. It should be noted also that the electron gains much faster near $\omega=\nu_m$. Since the collision frequency is pressure dependent, the minimum field needed to break down the gas can be expected at about the pressure for which $\nu_m=\omega$.

III. EXPERIMENTS

In these experiments, it was decided to determine experimentally the breakdown characteristics of a practical structure. Specifically, an open end waveguide antenna was used, although this geometry yields a complicated field configuration and no exact solution is available. However, one treatment of the near field of this type antenna is given by Fante and Mayhan[8]. Theoretical treatments of the effects of non-uniform fields have been given by Epstein[9] and Mayhan and Fante[10], but were only moderately successful. One of the major difficulties in treating problems theoretically is that the electron energy distribution functions are very complicated and the ionization and diffusion coefficients must be calculated from these distribution functions. In the analysis given here, only average values of ionization and diffusion coefficients are used.

Diagrams of the experiment and instrumentation are shown in Figs. 1 and 2. The antenna was mounted in a 6-inch brass flange which sealed the vacuum bottle. The waveguide was sealed from the vacuum bottle by a thin mica window seal on the inside surface of the flange. A thin, 0.001 inch thick, copper gasket provided good electrical contact between the window mount and the brass flange. This antenna, with the mica window, had a VSWR of approximately 1.5 with a corresponding reflection coefficient of 0.2. The X-band magnetron could be pulsed at rates over

a range covering from 10 to 500 pulses per second. The power delivered was controlled roughly by varying the high voltage applied to the magnetron and fine tuned by four flap attenuators in the waveguide line.

Since the power needed to maintain breakdown was the measured quantity, the discharge had to be started. Although the microwave power was often enough to do this, a spark source, approximately 2 cm from the antenna as shown in Fig. 2 was used, if necessary, to start the discharge. This was especially needed at low pulse rates. The microwave absorbent material and copper screening shown in Fig. 2 were to protect people in the room from the radiation.

In the experiments, microwave power was generated at 9.375 GHz and at pulse rates of 500, 100, 50, 20 and 10 pulses per second. The power was fed to the open end waveguide antenna, which radiated into the bottle. Crystal detectors were used, as shown in Fig. 1 to monitor the power incident on the antenna, the power reflected from the antenna and the power transmitted through the bottle. When the gas broke down, the transmitted power decreased sharply and, of course, the reflected power increased sharply. This was used as the criterion for breakdown detection and corresponded to the electron density reaching the level at which the plasma frequency equaled the applied frequency, which, in this case, amounted to $n \approx 10^{12}$ electrons/cm^3. The power was then reduced to the level at which breakdown just could be maintained, which could be seen by comparing the transmitted pulsed shape with the incident pulse shape. When breakdown occurred at the end of the pulse, the transmitted pulse would show a part missing. This is shown in Fig. 3 in an oscilloscope photograph.

As shown in Fig. 1, a small part of the incident power was coupled off by a directional coupler and fed through an attenuator to a thermistor power meter. Having first calibrated the directional couplers, attenuator and thermistor mount at 9.375 GHz, the average

incident power could be determined from the average power reading at the thermistor, and the peak power could be determined from the average power reading, the pulse rate, and pulse width. In the theory, a square pulse shape of width τ was always assumed. Such ideal pulses, of course, are not obtained in practice. As pointed out in Ref. 3, the pulse shape can be approximated by a trapezoidal shape. The effective pulse width then is somewhat longer than the level at which peak power is maintained. In these experiments, the pulse width was measured at approximately 70% of the maximum pulse height. The errors introduced by treating the pulses shown in Fig. 3 as trapezoidal pulses should be very small.

The power radiated from the antenna was calculated using the incident power, the measured VSWR to calculate the reflected power, and assuming no power was dissipated in the window. From Poynting's Theorem, the power radiated by an antenna is given by

$$P = \varepsilon_o c \int_A E_{rms}^2 \, dA \tag{6}$$

where ε_o is the permittivity of free space, c is the velocity of light and the integration is carried out over the area of the antenna. In this case, the field distribution was assumed to be that of the TE_{01} mode, so the integration gives

$$P = 1.33 \times 10^{-3} \, E_{rms}^2 \, A \tag{7}$$

Here, P is in watts if $E_{rms}^2 A$ has the units of $(\text{volts})^2$. E_{rms} is the rms value of the electric field strength at the center of the antenna. Using this relation, the transmitted power measurement was converted to electric field strength at the center of the antenna.

The derivation of Eq. (7) ignores the effects of edges on the near field configuration, yet the data plotted in Figs. 4-8 compares well with that taken by other investigators. Fante and Mayhan[8] have shown that the field strength outside the aperture can be written as

$$E = E_x = E_o \cos\left(\frac{\pi y}{2B}\right)\left[1-2\pi\,\frac{z}{L}\right] \qquad (8)$$

where 2B is the width of the aperture parallel to the y axis, x is the axis parallel to the height of the guide, z is the distance from it and L is an effective length. This neglects the z component of the field which is important only at the top and bottom edges of the aperture. In any case, the field is strongest directly at the aperture where its configuration is nearly the same as the TE_{01} mode. The good agreement between the breakdown electric field versus pressure curves taken at 500 pulses per second in Air and those reported by other investigators (Refs. 1 and 7) was taken as confirmation that this approximation was fairly good.

For each gas, tests were run using the pulse rates of 10 to 500 pulses per second and measuring the power levels needed to maintain the discharge. At the high pulse rates, the average power was measured by the thermistor power meter. From this, the peak power was calculated and from that, the electric field in the center of the aperture was found as described. At the same time, the crystal response was noted, and thus, a calibration curve for the crystal was obtained. Subsequently, at the slowest pulse rates, where the power meter could not be expected to be accurate, the power could be measured from the crystal response.

The results of the breakdown tests are shown in Figs. 4-8. These are compared with breakdown fields calculated from data reported by Scharfman and Morita[7] in Figs. 4-8. For Air, considerable data is available on ionization frequencies[1,7,13,14]. The calculated breakdown curve shown in Fig. 4 was obtained from data from Scharfman and Morita[7] and from Light and Taylor[13]. This curve was in very close agreement with one calculated from McDonald's data[1], though at the low pressure end (0.3 Torr) the agreement between the experimental points and the curve calculated from McDonald's data was slightly better. For Carbon Dioxide

and Methane, no such data was available for comparison.

In order to calculate the breakdown curves, Eq. (3) was used. First, the characteristic diffusion length, Λ, in these experiments, was calculated to be approximately 0.34 cm. This is an average value since it is not a clearly defined quantity for this geometry, but does not vary by more than a few percent from this value. Then, the diffusion coefficients for the different gases were calculated as follows: It is known from kinetic theory that for electrons in a gas, the free diffusion coefficient, $D = \frac{2\bar{U}}{3m\nu_m}$, where $\bar{U}$ is the average energy of the electrons and ν_m is the electron collision frequency for momentum transfer. Now, it is argued that the average energy $\bar{U}$ is directly proportional to the ionization potential of the molecules in the gas because electrons with energies greater than the ionization potential will quickly lose it in ionizing collisions[5]. Therefore, the velocity distribution function $\varphi(v)$ will be almost a step function

$$\varphi(v) = \text{constant} \qquad v < v_i \qquad (9)$$

$$\varphi(v) = 0 \qquad v \geq v_i$$

where $\frac{1}{2}mv_i^2 = U_i$ = ionization potential. Then, it is found that $\bar{v} = 3/4v_i$ and $\bar{U} = 9/16U_i$. Therefore, D can be said to be proportional to U_i/ν_m, and the values of diffusion coefficient, D, in different gases can be calculated from the value in Air, if the relative values of ionization potential and collision frequency, ν_m, are known. That is,

$$D_g = \frac{(U_i)_g}{(U_i)_{air}} \frac{(\nu_m)_{air}}{(\nu_m)_g} D_{air} \qquad (10)$$

where the subscript g refers to the gas in question.

The value of collision frequency, ν_{mg}, for electrons in the gas, may be found approximately from setting $\omega=\nu_m$ at the pressure for which the minimum breakdown field was measured as suggested in the basic theory and assuming $\nu_{mg} = C_g p$. From the data shown in Figs. 4-8, the values of

C obtained in this way are somewhat higher than generally accepted, so following a suggestion in Scharfman and Morita[7], the collision frequencies were also calculated relative to the accepted value for Air. This was done by noting the relative pressures at which the minimum in the breakdown fields were observed. Thus,

$$C_g = C_{air} \frac{(p_{min})_{air}}{(p_{min})_g} \tag{11}$$

where $C_{air} = 5.3 \times 10^9$. Using these approximations and the data of Figs. 4-8 for the high pulse rates, the results of Table I were obtained. The values of collision frequency for Argon and Nitrogen found in this way agree well with those found in Ref. 7.

One more assumption was needed to calculate the breakdown curves from Eq. (5) and that was the value of $\frac{n_b}{n_0}$. This was assumed to be 10^8. Since $n_b \approx 10^{12}$ electrons/cm^3, this amounted to $n_0 \approx 10^4$ electrons/cm^3. It is the logarithm of this ratio that is needed in Eq. (3), so the results were not very sensitive to this value. With this assumption and the calculation of the diffusion term at a given pressure, the necessary ionization frequency was obtained. Then, using the data of Scharfman and Morita[7], the effective electric field needed to obtain that ionization frequency was found and from the calculated collision frequency, converted to actual rms field strength. This was done at each pressure and the results plotted in Figs. 4-6. Since no data was available on Carbon Dioxide and Methane, no such curves could be obtained for these gases.

Equation (3) can also be used with the data in Figs. 4-8 to obtain curves of ionization frequency as a function of effective field. The same assumptions were made for diffusion coefficients, collision frequency and the ratio $\frac{n_b}{n_0}$, and the ionization frequency calculated for each pressure. Then, the breakdown field measured at 500 pulses per second was used and converted to effective field using the

calculated collision frequency. The results are plotted in Figs. 9-13, for the five gases and compared where possible with other data. In Fig. 11, which shows data for Nitrogen, comparison with data from Scharfman and Morita[7] and from Harrison[8] are included. The agreement between these sets of data and those derived from these experiments is seen to be fairly good.

A calculation of the loss rates of free electrons in the gas by attachment and diffusion indicated that essentially all free electrons should have been gone in times of the order of 10 milliseconds. Because of these calculations, it was expected that the breakdown field strengths would rapidly shift to the single pulse levels when the period between pulses was of the order of 10 milliseconds, i.e., 100 pulses per second. As seen in Figs. 4-8, the breakdown field strengths increased considerably, but it was still possible to maintain a discharge even at much slower pulse rates. In single pulse operation, however, it was not possible to generate a discharge although the breakdown field strengths at 10 pps were still below the single pulse levels.

Several processes should be considered in explaining the behavior at low pulse rates. First, consider the electron loss processes. Recombination losses depend on ion and electron densities. Attachment losses increase with increasing pressure, but diffusion losses decrease with increasing pressure, so combined they tend to cancel each other. To a first approximation, attachment and diffusion vary linearly with pressure and combined, they give a minimum loss rate at the medium pressures between 1 Torr and 10 Torr. However, long term loss rates are not well-known. The combined action of recombination, attachment and diffusion may lead to higher losses at pressures of 1 to 10 Torr, which could explain the double minimum observed in Figs. 7 and 8. These would not have a large effect until the pulse rate was so slow that the electron densities would be reduced to very low values. It may be noted in

Figs. 4-8 that the breakdown curves with two minima were found only in Methane, Carbon Dioxide and possibly Air. All these gases should have large attachment losses as will be discussed later. Nitrogen and Argon, on the other hand, should not exhibit attachment losses and the breakdown curves for them do not show the double minima (see Figs. 5 and 6).

A second consideration is, that since attachment is one of the major loss processes of free electrons in some gases, it would be expected that negative ions could play an important role. These ions could be long lived, but the extra electron would be relatively lossely bound. Therefore, they could be neutralized relatively easily thus yielding the necessary free electrons which would then dominate the ionization process. This process could possibly lead to curves with two minima, since the ions and electrons would exhibit different collision frequencies.

A complicating factor in considering diffusion losses in the discharge is that both free and ambipolar diffusion occur. At low electron densities, the electrons diffuse freely. When the electron density is above about 10^6 electrons/cm^3, ambipolar diffusion occurs; that is, the electrons and ions are restricted by electrostatic forces and must diffuse together. The result is that the ions diffuse faster and the electrons diffuse much slower. The ambipolar diffusion coefficient behaves approximately as

$$D_{amb} = D_{free}\left(\frac{m}{M}\right)^{\frac{1}{2}} \qquad (12)$$

where m/M is the ratio of electron to ion mass.

In the pulsed discharge both free and ambipolar diffusion occur. During the actual discharge the electron density is approximately 10^{12} elec/cm^3 at the aperture, so ambipolar diffusion is the controlling process there. Far away from the aperture the electron density would be much lower, thus free diffusion would occur. Also, during the pulse, as

the electron density in the aperture increases, the diffusion undergoes transition from free to ambipolar. It was assumed that free diffusion controls the onset of breakdown because it is much faster than ambipolar diffusion. For the same reason, it was assumed that ambipolar diffusion controls the loss of electrons by diffusion after the pulse. Therefore, the ambipolar diffusion coefficient given in Eq. (12) was used to calculate the diffusion loss rates.

IV. RESULTS AND CONCLUSIONS

The results of the measurements of the field strengths needed to maintain breakdown in Air, Argon, Nitrogen, Carbon Dioxide and Methane are shown in Figs. 4-8 for pressures between 0.3 and 30 Torr and at pulse rates from 10 to 500 pulses per second. For comparison, breakdown curves calculated from data reported by other investigators are shown where possible.

In all the gases, the peak power level at the slow pulse rates (10 pulses per second) could be raised substantially above that at the faster pulse rates (500 pulses per second). At the slow pulse rate the data showed an interesting effect in that there were two minima in the breakdown field strength versus pressure curves for Carbon Dioxide and Methane. The effect showed a large increase in the peak power radiated before a discharge would be sustained. This behavior was attributed primarily to the combination of the electron loss processes and the efficiency of heating the electrons.

Unfortunately, not much is known about electron loss processes at low densities, especially in Carbon Dioxide and Methane. Therefore, the data and explanations must be presented at this time without satisfactory proof. Any explanation must account for the following observations:

1. The process depends on pulse rate and has a time constant of

the order of 1/10 sec.

2. Significantly higher fields are required at the very low pulse rates.

3. The process is pressure dependent and some of the breakdown curves exhibit two minima.

4. At pressures below 1 Torr the breakdown fields at slow pulse rates closely matched those at faster pulse rates.

5. The effect was principally observed in CO_2 and CH_4.

The data taken at 500 pulses per second was used to calculate the net ionization frequency as a function of effective electric field. The results of these calculations are shown in Figs. 9-13. Again, data from other investigators is shown where possible. Generally, the ionization frequencies calculated from the measurements reported here fall above the other data. This might be attributed to impurities in the gases, since the purity level was not high in these tests.

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TABLE I

ELECTRON COLLISION FREQUENCIES AND DIFFUSION COEFFICIENTS

CALCULATED FROM ANTENNA BREAKDOWN DATA

Gas	Pressure at Minimum Breakdown Field p_{min} (Torr)	Collision Frequency ν_m/p (sec. Torr)$^{-1}$	Ionization Potential U_i (ev)	Free Diffusion Coefficient D_p (cm^2Torr/sec)
Air	8.2	5.3×10^9	12.5(O_2)	1.63×10^6
A	12.0	3.6×10^9	15.8	3.21×10^6
N_2	8.?	5.3×10^9	15.5	2.02×10^6
CO_2	7.5	5.8×10^9	13.7	1.63×10^6
CH_4	6.5	6.7×10^9	12.6	1.30×10^6

TABLE II

ELECTRON AFFINITIES

Gas	*Electron Affinity (ev)
A	-1.0
N	>0
N_2	<0
O	1.47
O_2	0.44
NO	0.91
N_2O	----
NO_2	1.6
CO_2	dissociative attachment
CO	dissociative attachment
CH_4	----
CH_3	1.13
CH_2	----
CH	1.6
H	0.8
H_2	0.9
C	1.3

*Values from Ref. 14, Chapter 8; and Ref. 15, p. E-73

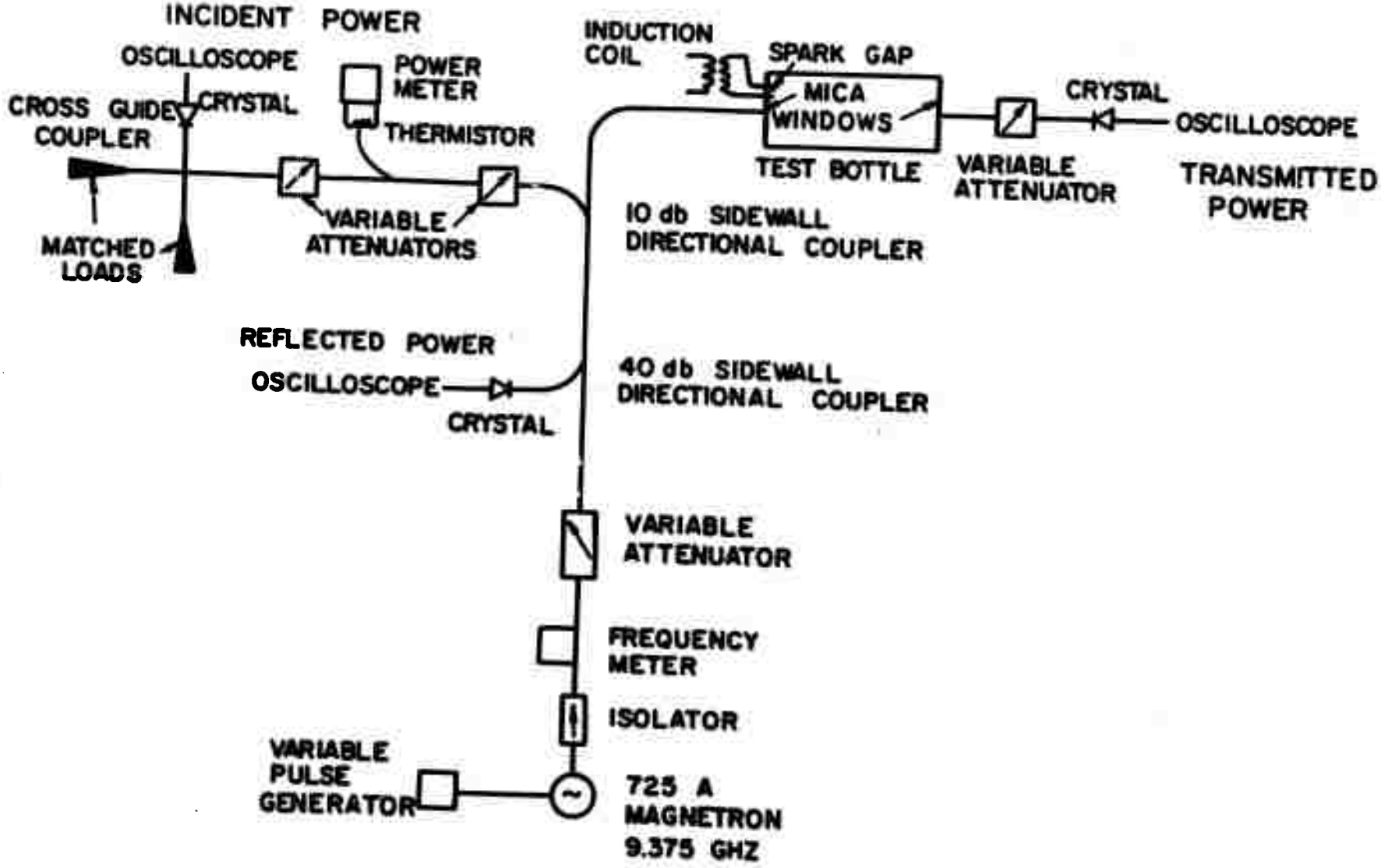

FIG. 1 SCHEMATIC FOR BREAKDOWN EXPERIMENTS

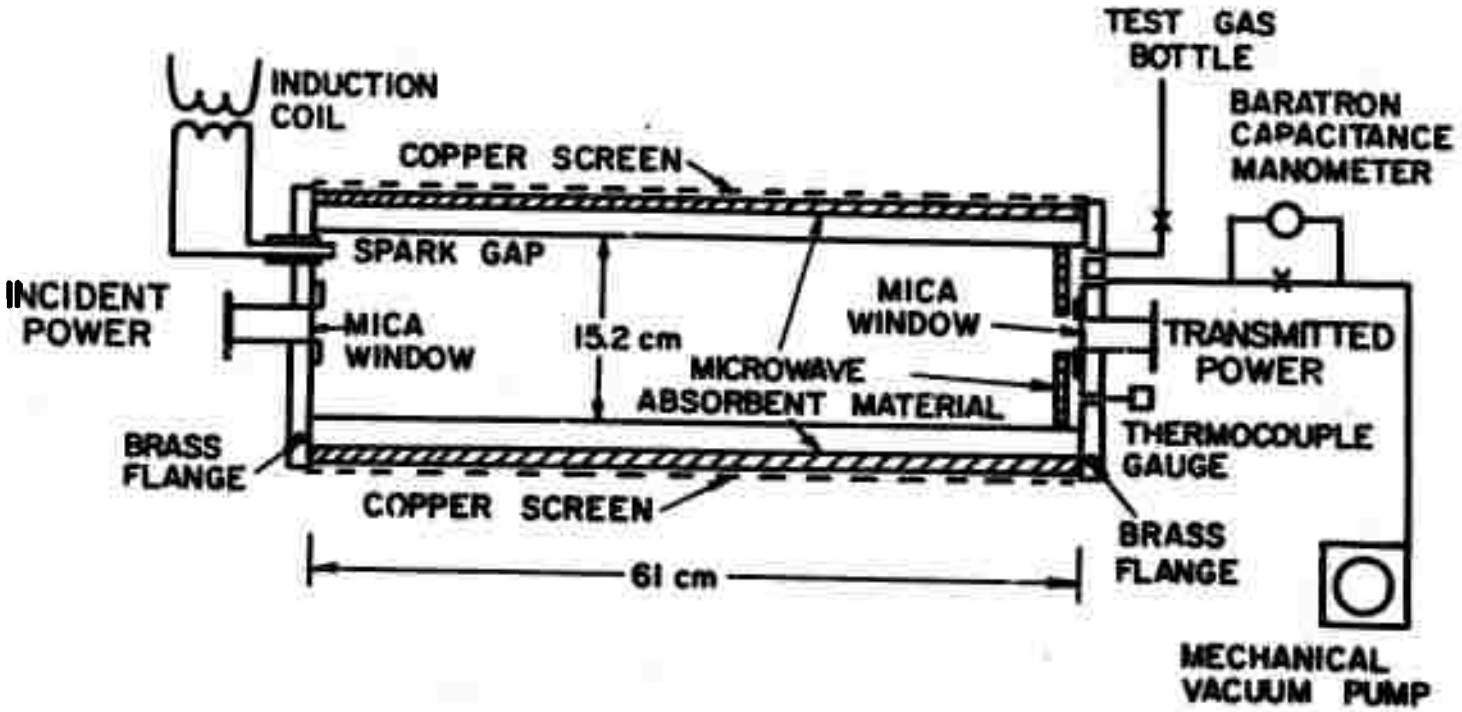

FIG. 2 SCHEMATIC DIAGRAM OF TEST BOTTLE FOR BREAKDOWN EXPERIMENTS

TIME 0.5 μSEC/BOX →

FIG. 3 INCIDENT AND TRANSMITTED PULSES RESPECTIVELY DURING BREAKDOWN AS MEASURED BY CRYSTAL DETECTORS

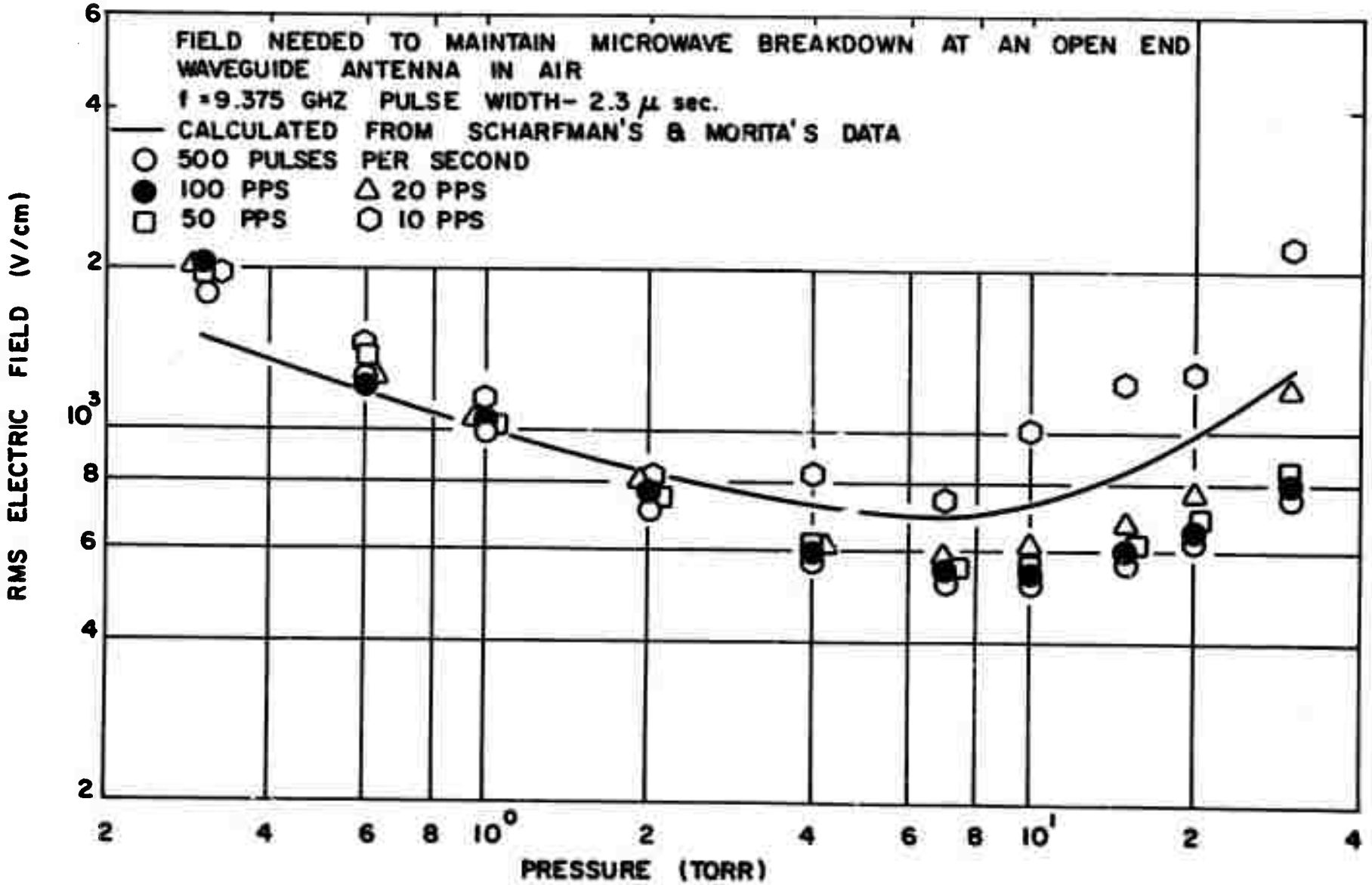

FIG. 4 PRESSURE E-FIELD BREAKDOWN FOR AIR

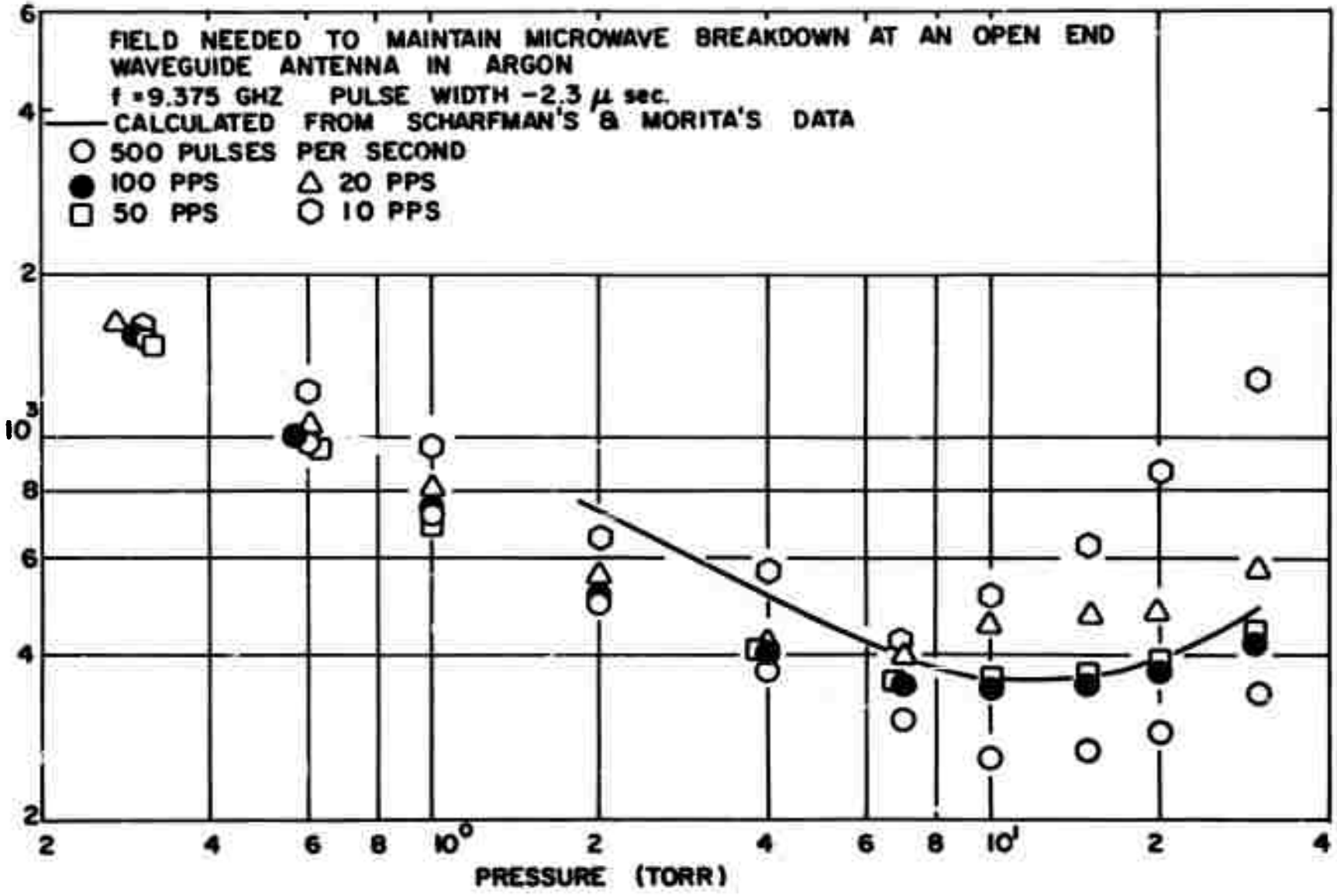

FIG. 5 PRESSURE E-FIELD BREAKDOWN FOR ARGON

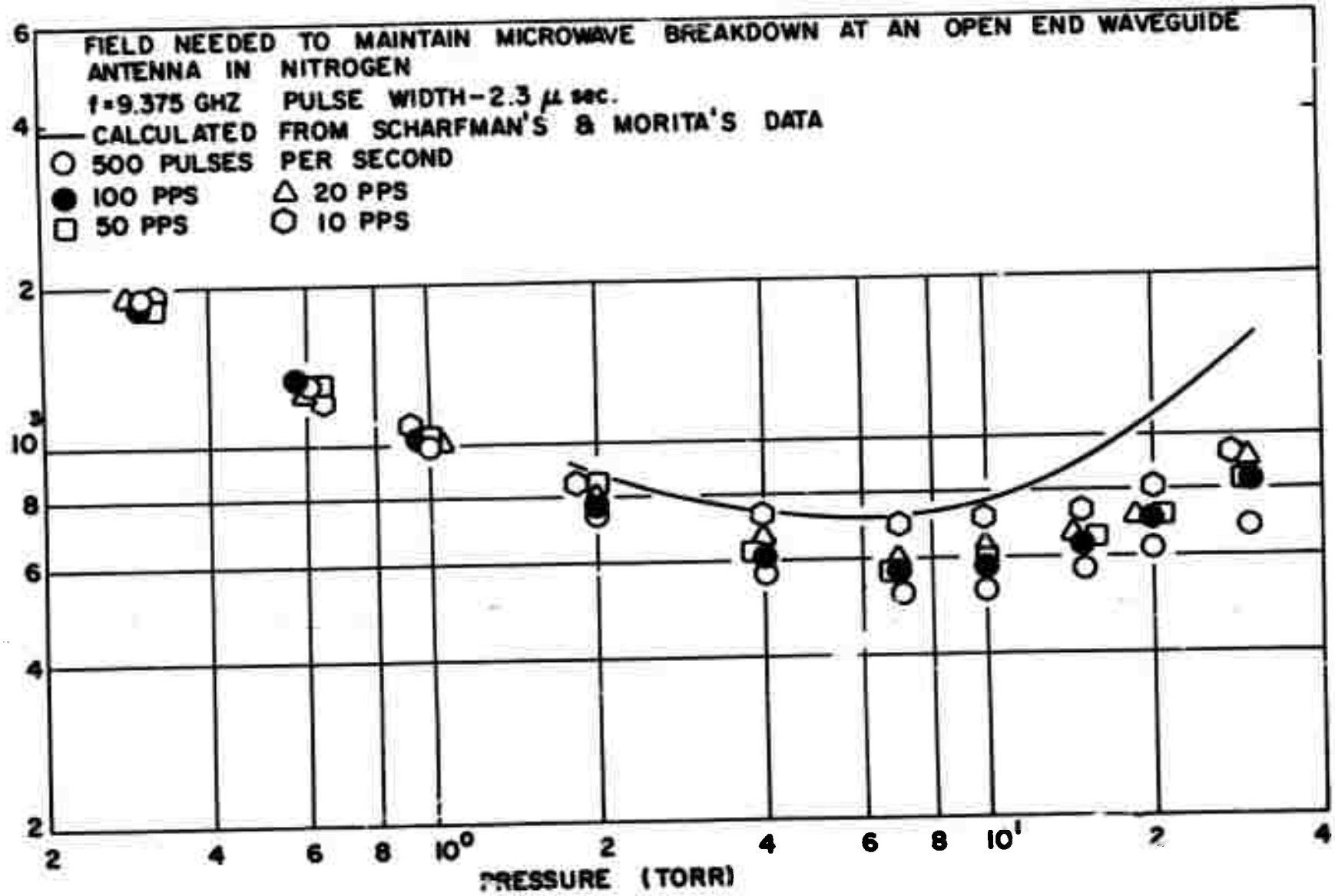

FIG. 6 PRESSURE E-FIELD BREAKDOWN FOR NITROGEN

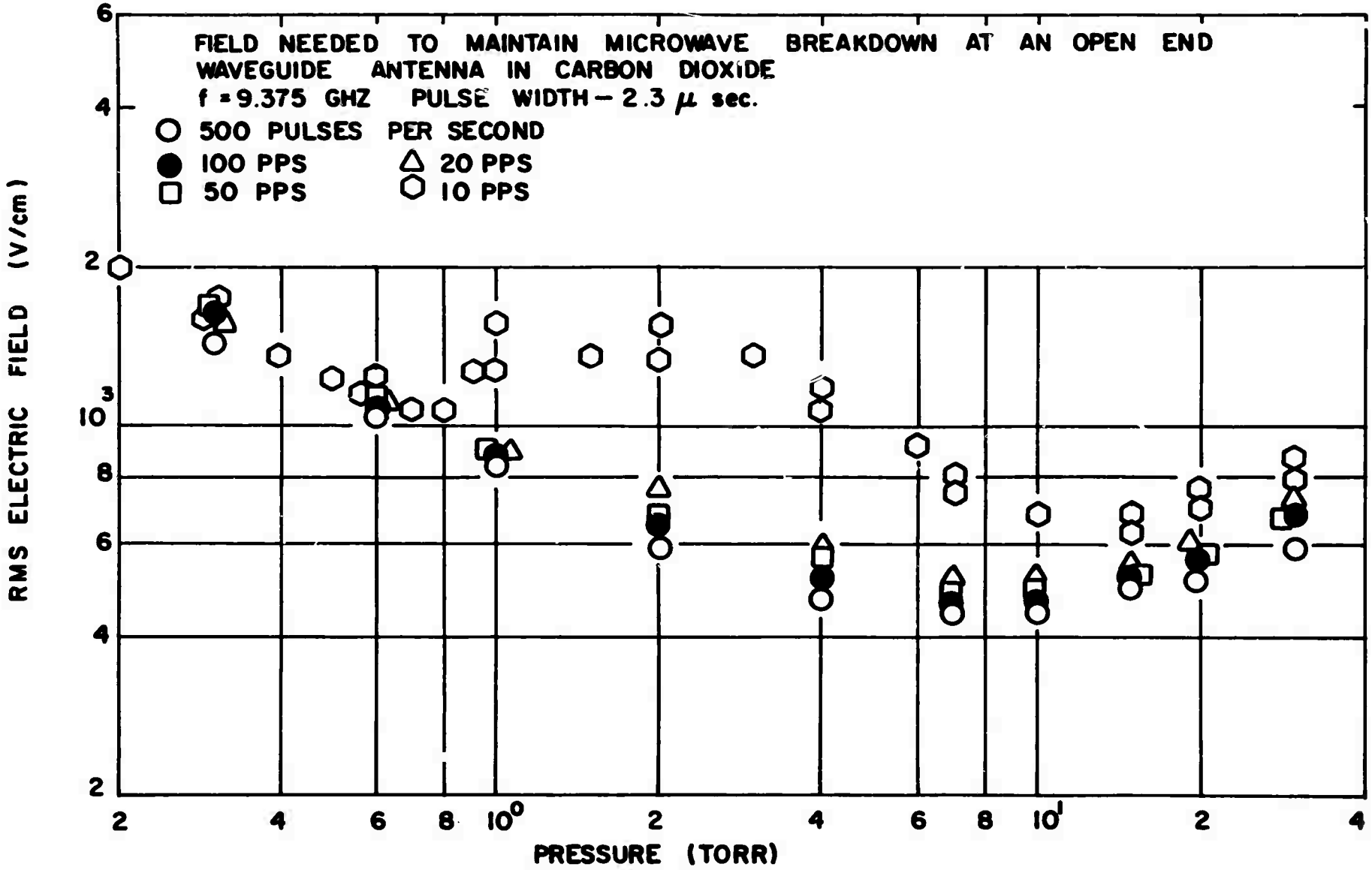

FIG. 7 PRESSURE E-FIELD BREAKDOWN FOR CARBON DIOXIDE

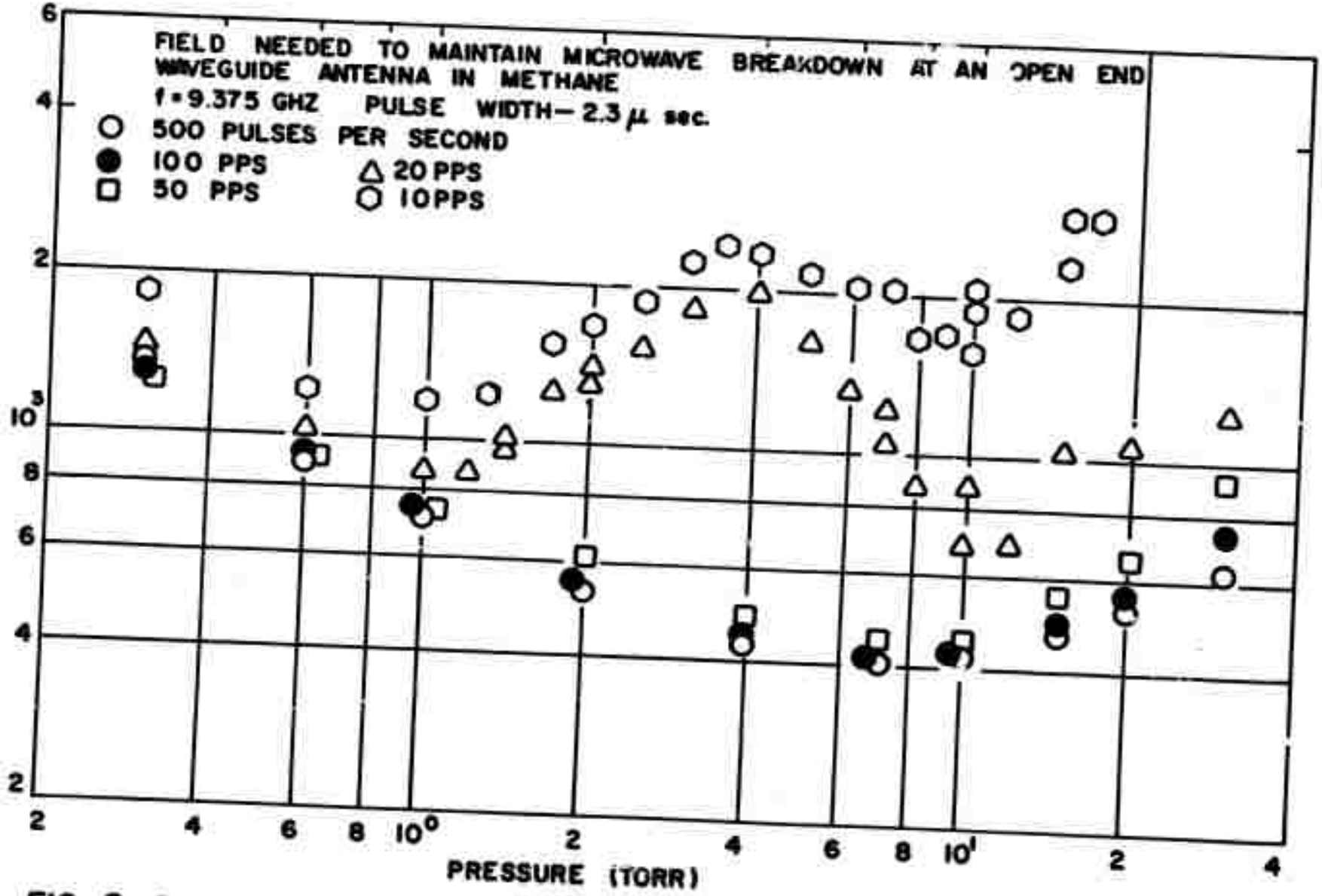

FIG. 8 PRESSURE E-FIELD BREAKDOWN FOR METHANE

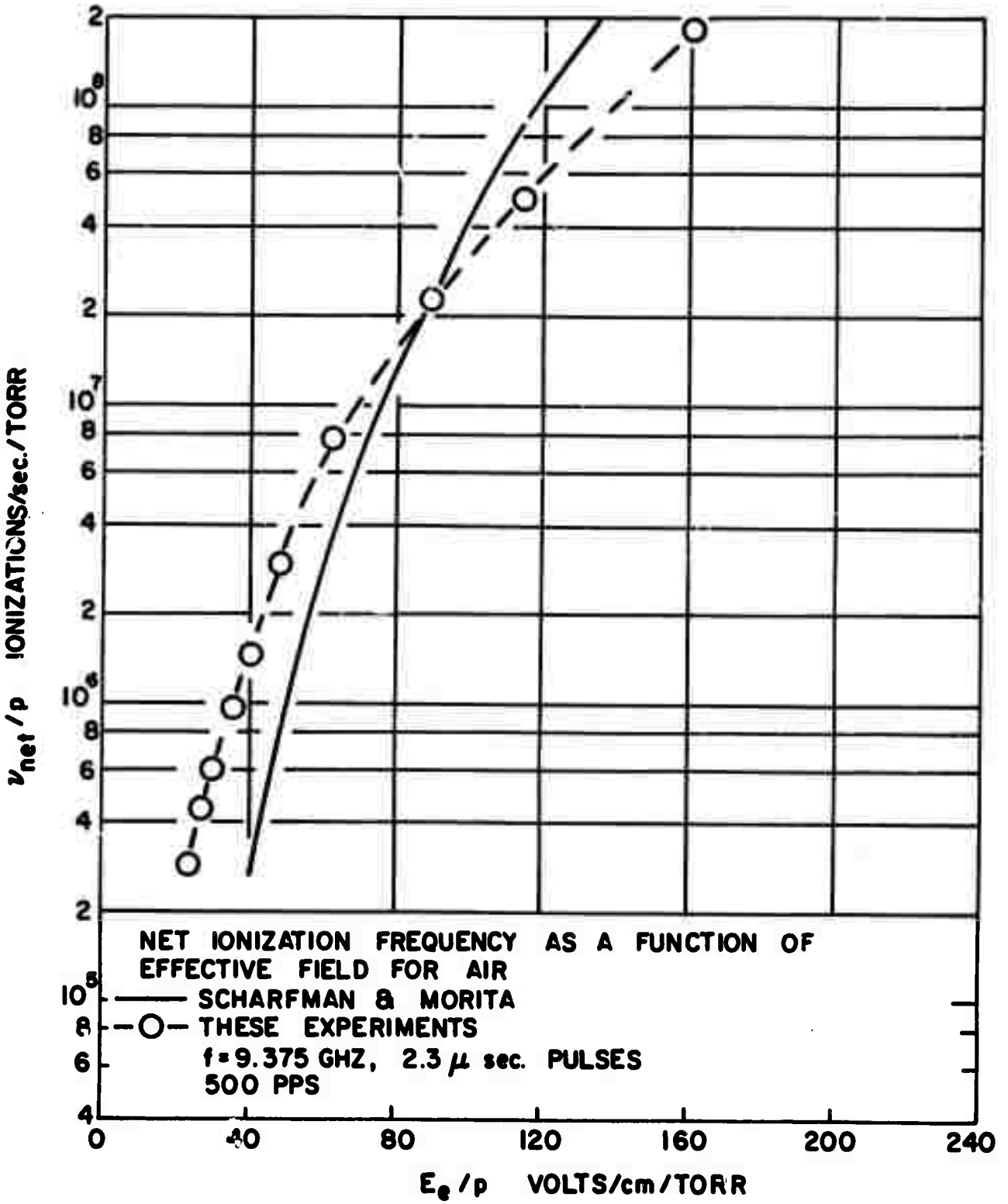

FIG. 9 IONIZATION FREQUENCY VS E-FIELD FOR AIR

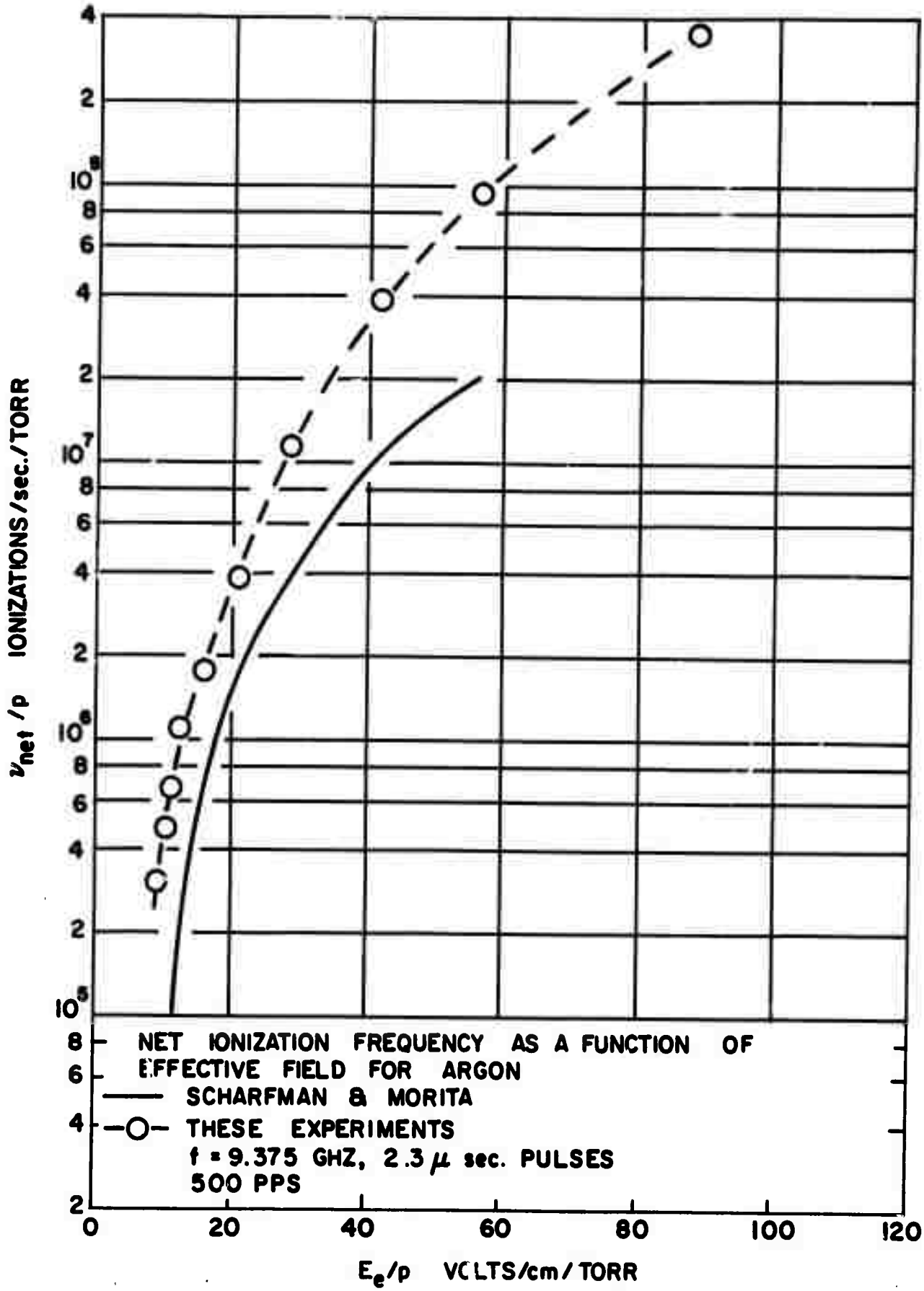

FIG. 10 IONIZATION FREQUENCY VS E-FIELD FOR ARGON

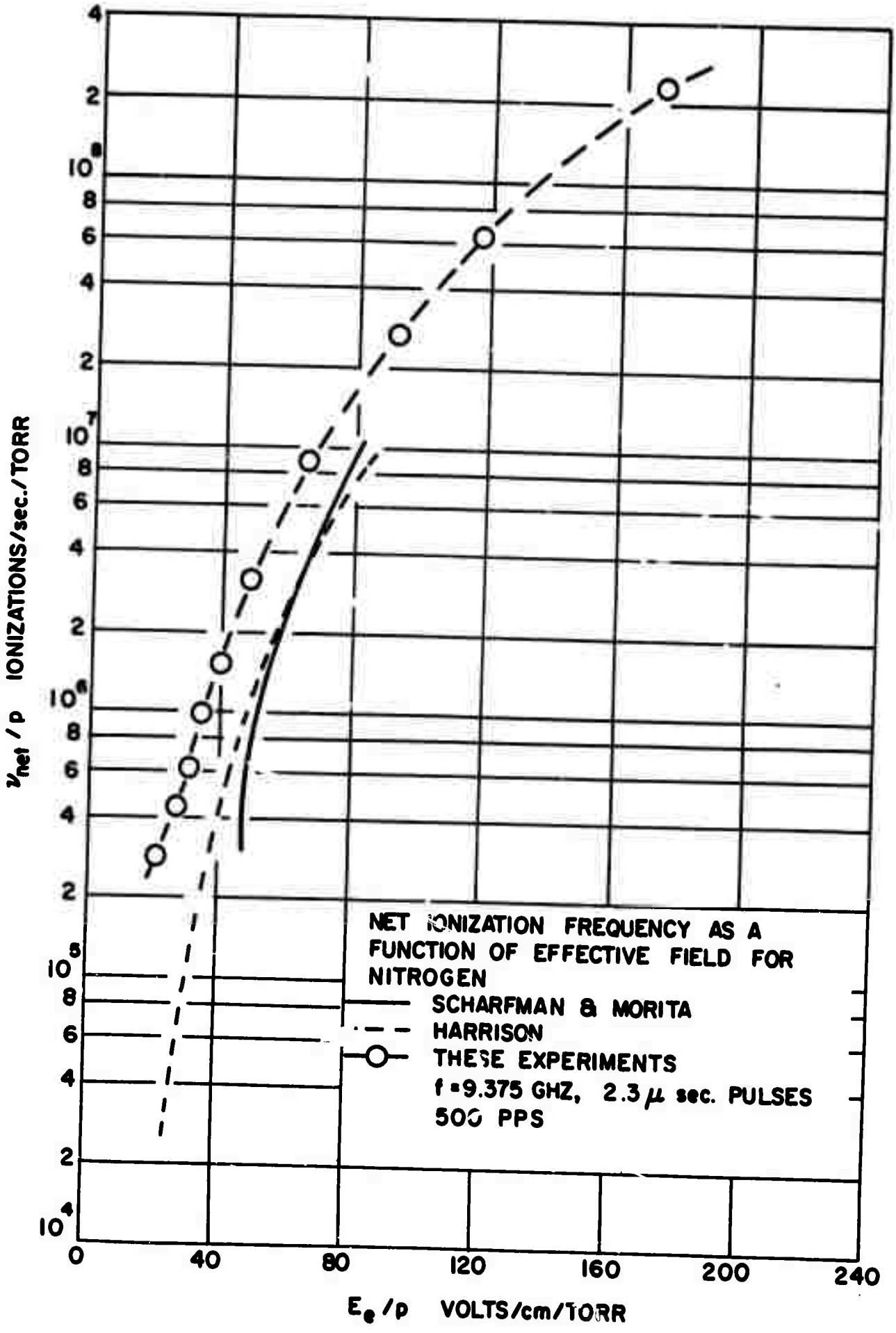

FIG. 11 IONIZATION FREQUENCY VS. E FIELD FOR

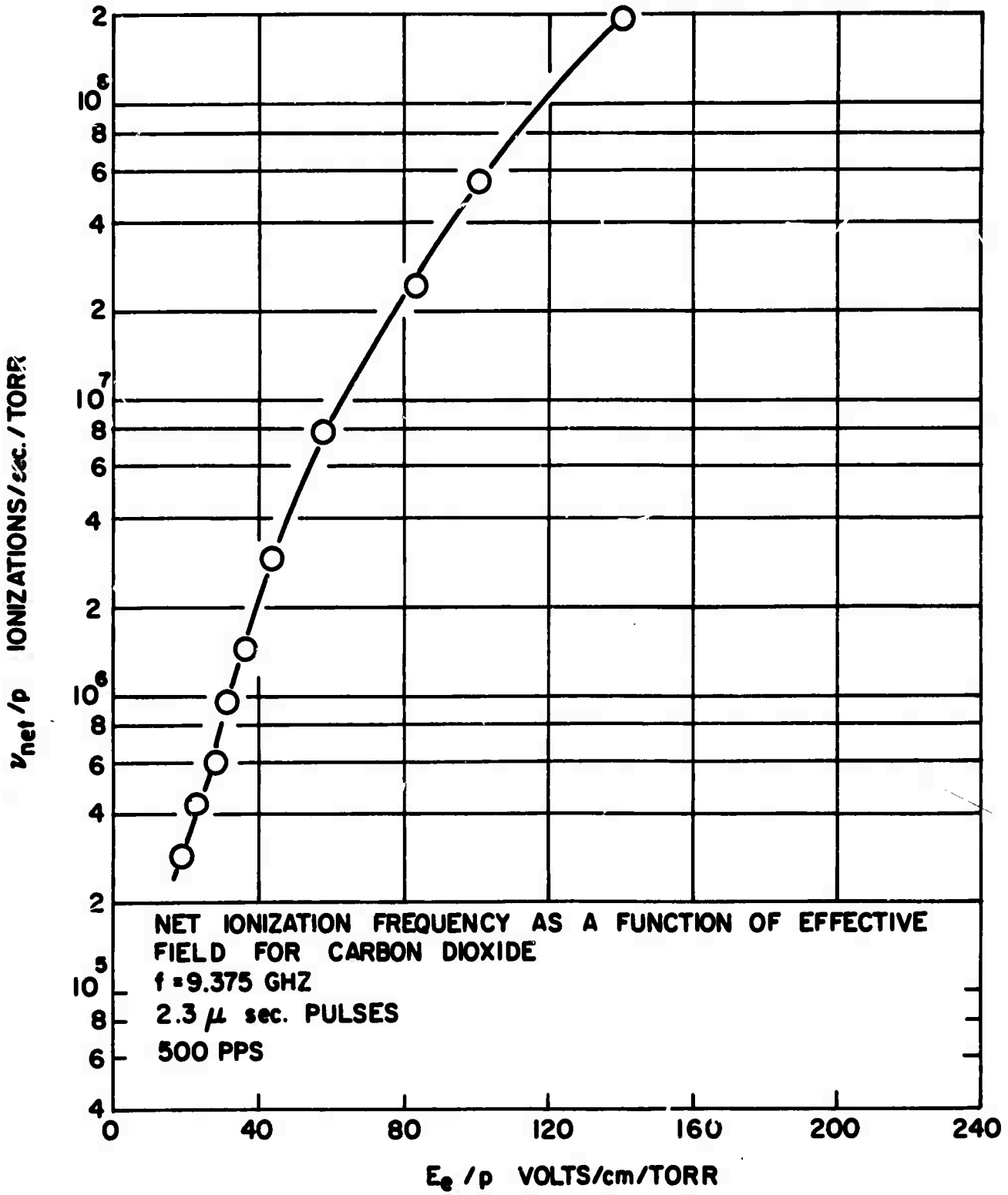

FIG. 12 IONIZATION FREQUENCY VS E-FIELD FOR CARBON DIOXIDE

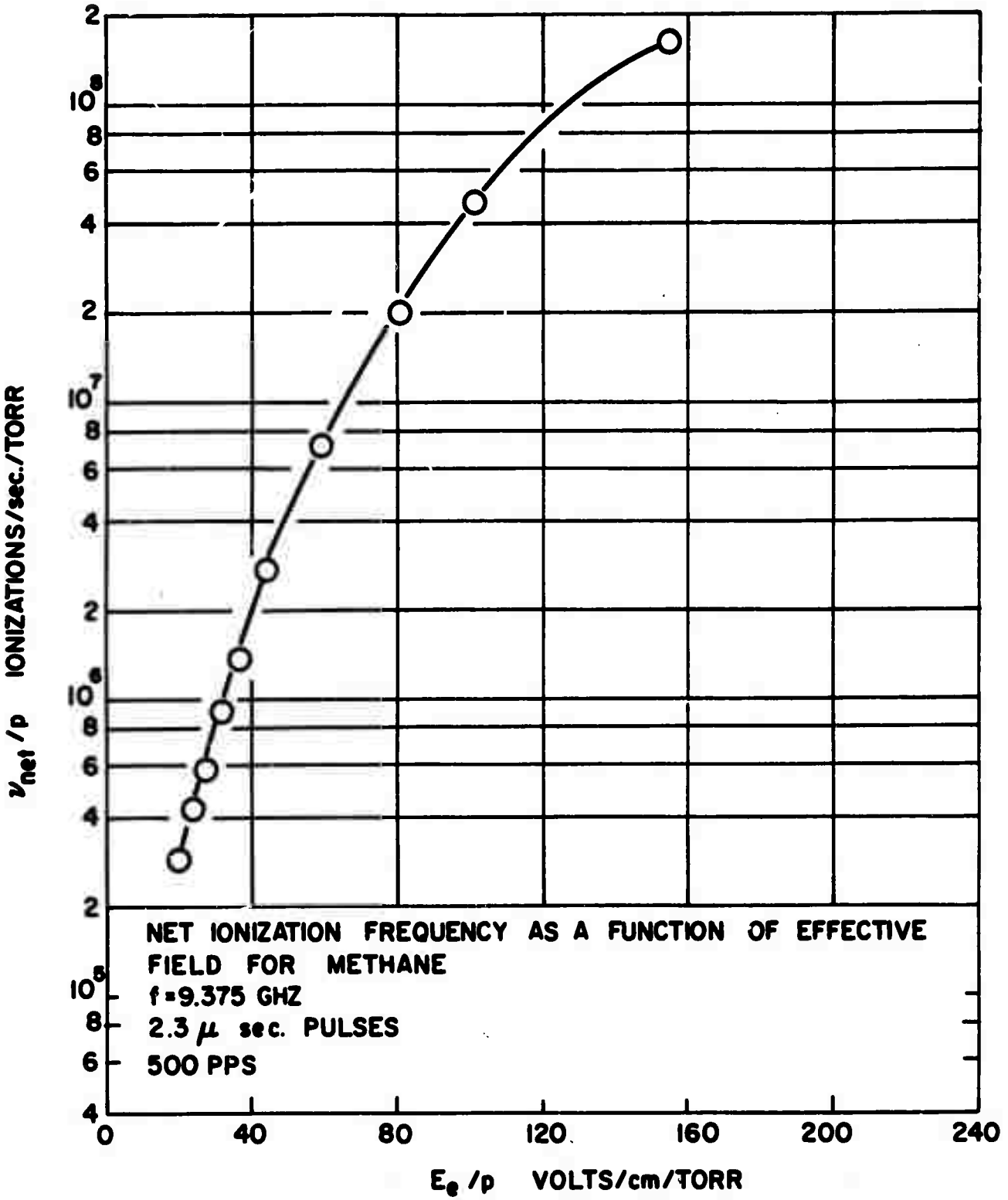

FIG. 13 IONIZATION FREQUENCY VS E-FIELD FOR METHANE