Short-pulse high-power microwave propagation in the atmosphere

C. A. Sullivan, W. W. Destler, J. Rodgers, and Z. Segalov
Electrical Engineering Department and Laboratory for Plasma and Fusion Energy Studies, University of Maryland, College Park, Maryland 20742

(Received 12 November 1987; accepted for publication 12 February 1988)

The propagation of high-power (10–200 kW/cm^2) short-burst (3–30 ns) microwave pulses in the atmosphere has been studied experimentally. Microwave power from a large orbit gyrotron operating at 9.6 GHz is focused by a large-diameter parabolic reflector into a test cell. The ambient pressure in the test cell was varied over a wide range and the microwave power density necessary for atmospheric breakdown has been determined as a function of ambient pressure and pulse duration. Measurements of the microwave pulse duration before and after breakdown have been obtained to determine the extent to which microwave energy is absorbed or reflected by the breakdown plasma. Results are compared with available theory and previously reported experiments.

I. INTRODUCTION

Although microwave breakdown of the atmosphere has been a subject of study for many years,[1–10] considerable new interest has recently developed in the field arising from the availability of very high-power microwave sources developed for directed-energy systems and high-power radar applications. In particular, data obtained from experiments investigating microsecond-pulse rf breakdown in air have supported theoretical predictions that very high microwave power levels could be propagated in the atmosphere if the pulse duration could be made sufficiently short. It has also been proposed that at low ambient pressures a very high-power microwave pulse might accelerate free electrons to energies in excess of that associated with the peak in the ionization cross section for air in a distance short compared to a mean free path. In this manner even higher microwave powers might be propagated without breakdown.

Considerable theoretical and experimental work has been reported in this area in recent years.[11–17] Theoretical results reported by Woo and DeGroot,[11] Yee *et al.*,[12] and Ali and Coffey[13] have indicated that when breakdown occurs, an ionization front is rapidly formed which moves toward the microwave source and consequently decouples the microwaves from the initial breakdown region. In addition, the amount of energy that can be transmitted through the medium was found to be a strong function of the initial energy of the pulse and its frequency, pulse shape, and duration.

Several experiments have been reported in which the propagation of short-burst microwaves through air has been studied.[14–17] Bollen *et al.*[14] have reported studies of microsecond-pulse microwave breakdown in nitrogen by focusing the output of a 112-kW, 35-GHz gyrotron into a test cell. Breakdown was observed at microwave power densities of about 30 kW/cm^2 at ambient pressures below 75 Torr. Yee *et al.*[12] have reported studies of short-pulse (10 ns) microwave breakdown of air in a rectangular waveguide powered by a 15-MW *S*-band klystron operating at 2.856 GHz. Results of this study were found to be in good agreement with theory and simulation. Experimental results of Gould and Roberts[15] and Tetenbaum, MacDonald, and Bandel[16] employed *S*-band sources with repetition rates of 1200 and 20 pulses per second, respectively. In these cases the test cell was a resonant cavity fed by waveguide. Finally, recent work by Armstrong *et al.*[17] has been reported in which high-power microwaves from an *S*-band relativistic magnetron have been used to study breakdown thresholds. In these experiments, 6-ns microwave pulses were focused by a parabolic reflector into a test cell and the resultant breakdown observed using optical diagnostics.

In this paper, we report the results of an extensive experimental study of short-burst high-power microwave propagation through air. Data have been obtained for transverse electromagnetic (TEM) microwave pulse propagation in a test cell large enough to ensure that surface breakdown does not occur to any significant extent. Furthermore, data have been obtained over a wide range of microwave pulse power densities and pulse durations and for an equally wide range of ambient test-cell pressures. Section II contains a review of available theory relating to these experiments. Section III discusses the experimental apparatus used for the study, and results are presented in Sec. IV. Conclusions are drawn in Sec. V.

II. THEORETICAL DISCUSSION

The theory of microwave breakdown of a neutral media has been extensively treated in early work by MacDonald.[3] It is assumed that breakdown occurs when the electric field of the wave accelerates free electrons in the media to energies sufficient to ionize neutral species and initiate an avalanche process that produces a rapid increase in the plasma density. The continuity equation for electrons in the media can be written

$$\frac{\partial n}{\partial t} = \nu_i n - \nu_a n + \nabla^2(Dn), \qquad (1)$$

where n is the electron density, ν_i is the ionization rate, ν_a is the attachment rate, and D is the electron diffusion coefficient. The diffusion term can be approximated as $\nabla^2(Dn) \cong n(-D/\Lambda^2)$, where Λ is the characteristic diffusion length and depends upon the system geometry. Using this approximation, the continuity equation has a solution

$$n = n_0 e^{(\nu_i - \nu_a - D/\Lambda^2)t}, \qquad (2)$$

where n_0 is the initial free-electron density. The diffusion coefficient D was found[3] to follow the empirical relation

$$Dp = [29 + 0.9(E/p)] \times 10^4, \qquad (3)$$

where p is the ambient media pressure and E is the amplitude of the wave electric field. MacDonald noted that in cw microwave breakdown phenomena steady state is reached and

$$\nu_i - \nu_a = D/\Lambda^2. \qquad (4)$$

He then matched these results to data obtained from cw microwave breakdown experiments conducted in a cavity. In this manner he obtained estimates of the net ionization rate $\nu_i - \nu_a$ as a function of ambient media pressure for the given wavelength and electric field amplitude.

For pulsed microwave breakdown, Eq. (4) does not apply and the electron density grows at a rate given by

$$\nu = \nu_i - \nu_a - D/\Lambda^2. \qquad (5)$$

A reasonable estimate of the time taken to achieve breakdown will be obtained if it is assumed that breakdown occurs as the plasma density approaches the critical plasma density,

$$n_p = 10^{13}/\lambda^2 \text{ cm}^{-3}. \qquad (6)$$

The pulse duration τ for breakdown to occur can then be determined approximately from

$$n_p = n_0 e^{\nu\tau}. \qquad (7)$$

Experimentally, the initial free-electron density is not usually known to any degree of accuracy, but the exponential nature of the rise in the electron density with time tends to minimize the effect of errors in the number assumed for n_0. In addition, studies by Rappaport, Latham, and Striffler[18] have indicated that wave propagation can be significantly affected by plasma densities considerably below the critical plasma density, although the exponential nature of the density increase with time minimizes errors resulting from this assumption as well.

In a similar approach, Ali and Coffey[13] theoretically studied breakdown by treating electrons with a Maxwellian velocity distribution. In this work the average electron energy was assumed to be linearly dependent on E/p. They assumed that the ionization in air is primarily from the oxygen molecule and used known values for the attachment frequency and estimates for the diffusion scale length Λ to determine the net ionization rate as a function of ambient pressure and pulse duration.

In addition to this analytical work, significant numerical simulation has been conducted of short-pulse microwave propagation in the atmosphere,[11,12,14] results in reasonable agreement with experiment where data are available.

III. EXPERIMENTAL APPARATUS

High-power microwave pulses used for the propagation studies were generated by a large-orbit gyrotron[17,18] operating at 10 GHz. This device, powered by a pulse line accelerator [2 MeV, 10–20 kA, 30 ns full width at half-maximum (FWHM)], produces high-power microwave radiation (100–500 MW) by the resonant interaction of the modes of an axis encircling rotating electron beam with the modes of a magnetron-type multiresonator circuit. The rotating electron beam is produced by passing a cylindrical, nonrotating beam from a field emission diode through a narrow magnetic cusp, as shown in Fig. 1. The cusp acts to convert the upstream electron axial velocity (v_{z1}) into a downstream azimuthal ($v_{\theta 2}$) and axial velocity (v_{z2}) in a manner given approximately by

$$v_{z1}^2 = v_{z2}^2 + v_{\theta 2}^2 = v_{z2}^2 + r_0^2\omega_c^2. \qquad (8)$$

Here $\omega_c = eB/m\gamma$ is the relativistic electron cyclotron frequency, where e is the electronic charge, m is the electron rest mass, B is the axial magnetic field, and

$$\gamma = (1 - v^2/c^2)^{-1/2} \qquad (9)$$

is the relativistic mass factor for the beam electrons (c is the speed of light in vacuum). The radius r_0 is the mean radius of the rotating electron beam, which for a symmetric cusp is approximately equal to the cathode radius. Thus for a given applied axial magnetic field, only electrons with energies greater than a value given by

$$E_{\text{th}} = [(mc^2)^2 + c^2e^2r_0^2B^2]^{1/2} - mc^2 \qquad (10)$$

can pass through the cusp into the downstream drift region.

The above result allows for the use of this facility for the

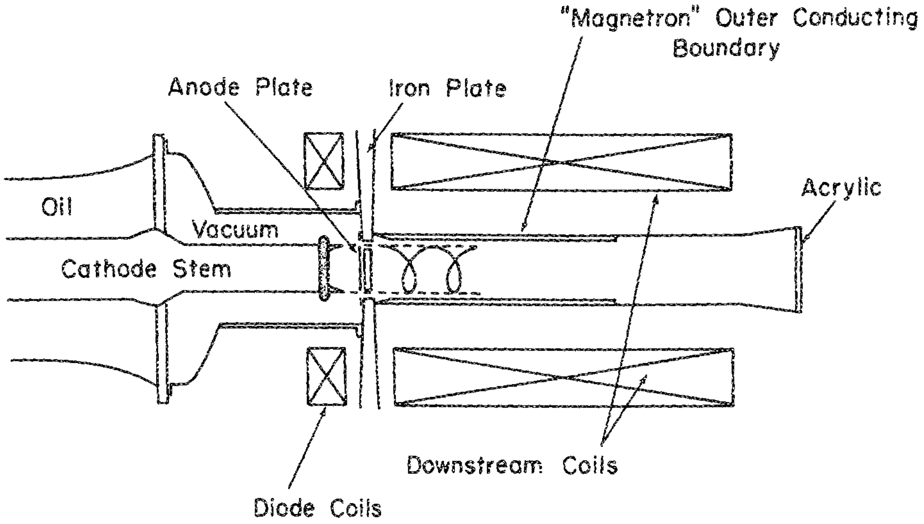

FIG. 1. Large orbit gyrotron experimental configuration.

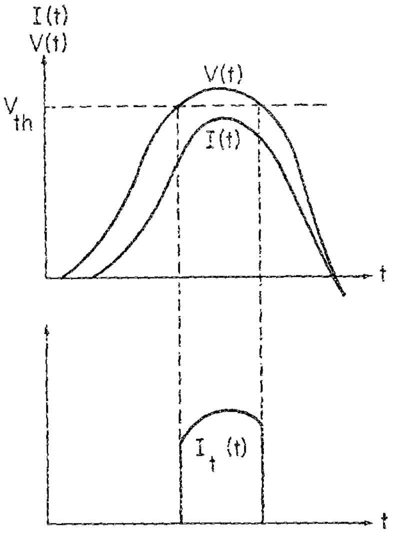

FIG. 2. Idealized upstream diode voltage and current waveforms (top) and downstream current waveform (bottom).

production of very short microwave pulses. Since the diode voltage waveform slowly rises to a maximum value and then slowly decays, the duration of the downstream electron beam pulse can be varied within certain limits by varying the applied axial magnetic field strength. In this manner all electrons with energies below that value required for transmission through the cusp are reflected and the downstream beam pulse can be considerably shorter in duration than the diode pulse, as shown in Fig. 2. Although optimum microwave production cannot be achieved over as wide a variation of magnetic field as might be desired, data have been obtained for microwave pulses of varying power in the range 3–30 ns (FWHM).

The experimental configuration used for the propagation experiments is shown in Fig. 3. Microwaves from the large-orbit gyrotron are focused by a large diameter (150 cm) parabolic reflector with a 75-cm focal length into a 30-cm-diam cylindrical acrylic vacuum chamber which served as the test cell. The test cell was fitted with a high-accuracy vacuum gauge and a calibrated leak valve that allowed maintenance of ambient pressures from atmospheric down to 0.1 Torr. Measurements of the microwave power density along the dish axis within the test cell are shown in Fig. 4. The points plotted are the averages of four shots taken at each position. In this way the effects of shot-to-shot variation in the microwave output power of the device can be minimized. Although the focusing of the microwaves into the test cell was not as effective as had been expected from low-power measurements, it was sufficient to ensure that breakdown, when observed, did not initiate on the test-cell walls. Surface breakdown, which is generally easier to initiate than bulk media breakdown, must be avoided if true media breakdown limits are to be established. The superposition of the incident wave from the source with the reflected wave from the parabolic reflector results in a small-amplitude standing wave in the cell, although measurements indicate that the incident microwave power is more than a factor of 10 lower than the reflected microwave power at the focus. No seed ionization source was used for these studies.

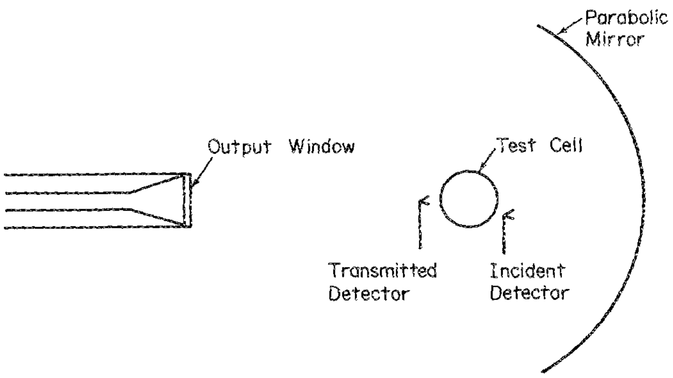

FIG. 3. Configuration used for microwave propagation studies.

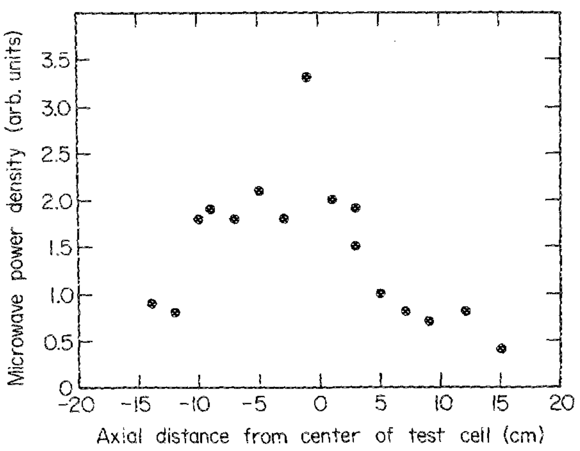

FIG. 4. Microwave power density vs axial distance from the center of the test cell. The test-cell diameter is 30 cm.

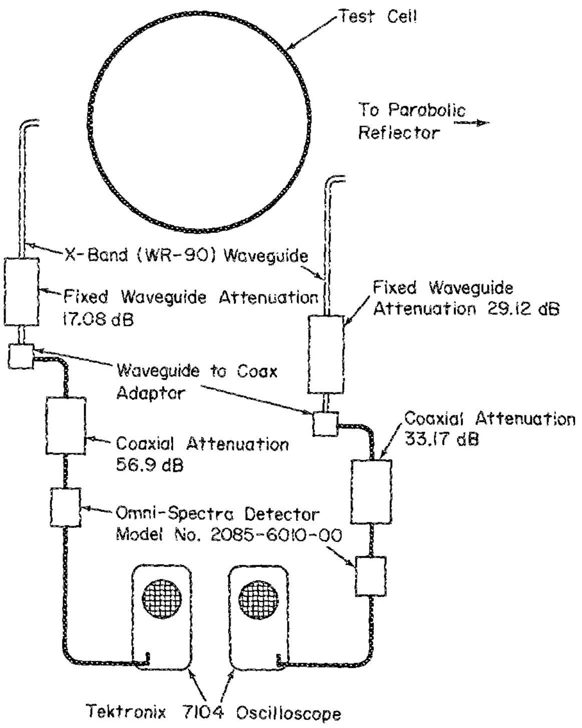

FIG. 5. Schematic of microwave diagnostic setup used in the propagation experiments.

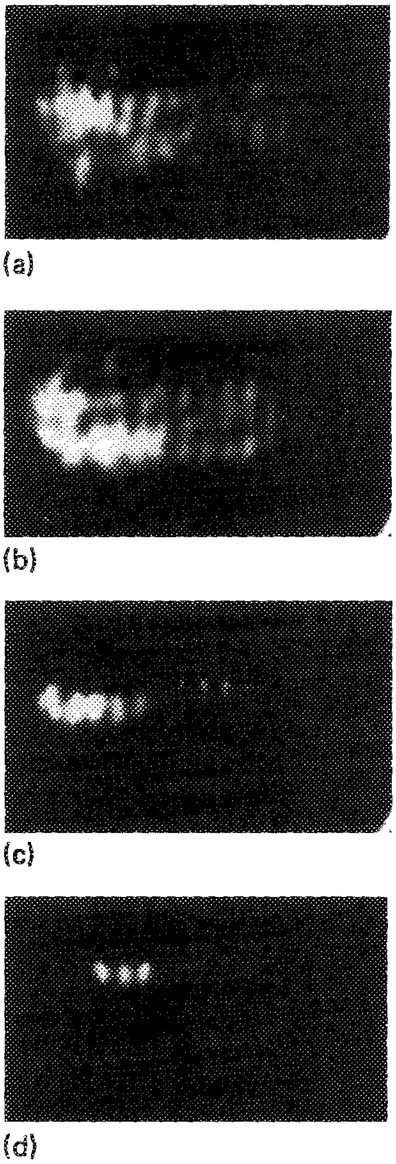

FIG. 6. Time-integrated photographs of microwave-induced breakdown in the test cell, (a) 4.8, (b) 9.5, (c) 20, and (d) 28 Torr.

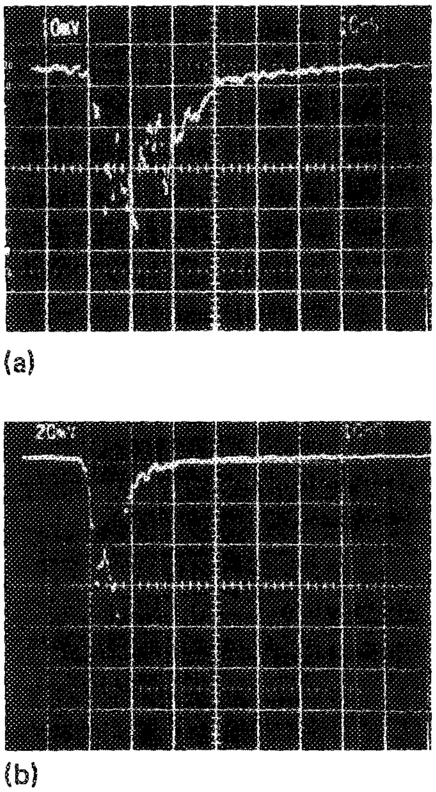

FIG. 7. Typical microwave detector waveforms, (a) incident detector, and (b) transmitted detector. Waveforms correspond to case (a) in Fig. 6.

Open-ended X-band (8–12 GHz) waveguide sections were used to detect the microwave signals before and after the focal point in the test cell, as shown in Fig. 5. The microwave signals were passed through calibrated fixed attenuators to calibrated detectors. All components were calibrated inhouse using standard techniques. The detectors chosen were selected on the basis of their measured transient pulse response time (rise time ~1 ns). Detector signals were fed directly into Tektronix 7104 fast oscilloscopes.

IV. EXPERIMENTAL RESULTS

In previous work,[12] the microwave pulse duration that could be propagated without breakdown was determined by simply measuring the duration of the post-breakdown microwave pulse. The experiments reported here were designed so that breakdown could be detected by two independent criteria. The pulse durations before and after the focal point in the test cell were compared to determine if microwave absorption and reflection by breakdown plasma had shortened the duration of the post-focus microwave pulse significantly. In addition, time-integrated photographs of the visible light produced by ionization processes in the test cell were obtained using a still camera. A typical set of photographs of breakdown in the test cell is shown in Fig. 6, and they clearly indicate that surface breakdown at the test-cell wall is not a significant factor in the measurements. For a fixed microwave power density and pulse duration, the breakdown region becomes progressively smaller as the ambient test-cell pressure is increased. At the higher pressures evidence of the small-amplitude standing wave in the test cell can be clearly seen in the photographs. The observed wavelength of the breakdown pattern is fully consistent with

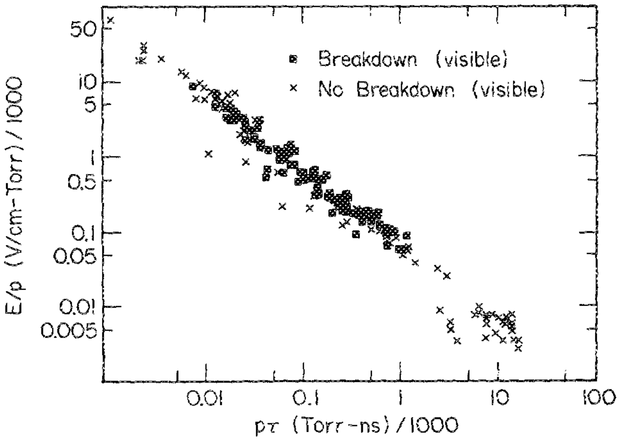

FIG. 8. Microwave propagation data plotted using the visible light criterion for breakdown.

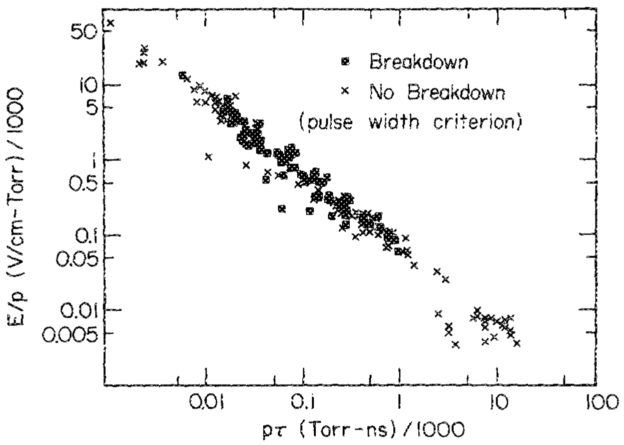

FIG. 9. Microwave propagation data plotted using the pulse width criterion for breakdown.

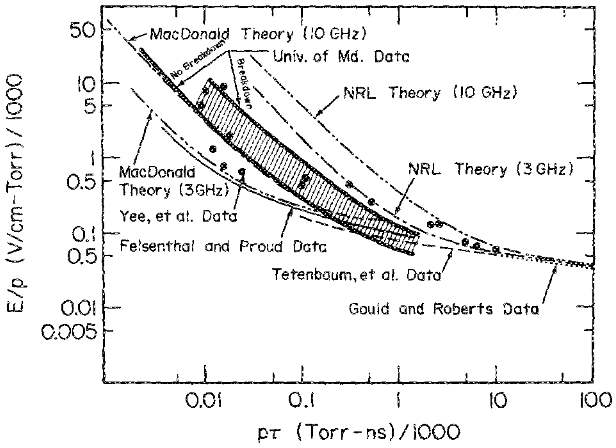

FIG. 10. Comparison of results of present study with available theory and experiment.

the operating frequency (9.6 GHz) of the large-orbit gyrotron.

A typical set of oscilloscope waveforms for the prefocus and post-focus detector systems are shown in Fig. 7. The examples shown are for a case where breakdown resulted in considerable shortening of the post-focus microwave pulse duration. Data from all experiments are plotted in the familiar E/p vs $p\tau$ format in Figs. 8 and 9. The data points in the two plots are the same, but in Fig. 8 the visible light criteria for breakdown was used to indicate on which shots breakdown occurred, and in Fig. 9 breakdown was defined by a measured post-focus pulse duration of 80% or less of the prefocus pulse duration.

V. CONCLUSIONS

From the data it is possible to draw a line on the E/p vs $p\tau$ plot above which breakdown always occurs and a second line below which breakdown never occurs. These results have been compared with data from experiments by Yee *et al.*,[12] Gould and Roberts,[15] Tetenbaum *et al.*,[16] and Felsenthal and Proud[10] in Fig. 10. Also shown are the predictions of theory by MacDonald[3] and Ali and Coffey[13] for wavelengths of 3 and 10 cm.

The data obtained in these experiments are in reasonable agreement with data obtained by Yee *et al.*,[12] for breakdown inside a waveguide at 2.85 GHz. The results are also in reasonable agreement with the theory of MacDonald.[3] Both the present data and the data of Yee *et al.* fall somewhat below the theoretical predictions of Ali and Coffey, although the qualitative agreement between theory and experiment is very good. It is interesting to note that no seed ionization source was employed in these experiments, in contrast to the experiments reported by Yee *et al.*[12] and Gould and Roberts.[15] Usually, seed ionization sources are used to provide a reliable source of small numbers of free electrons to impove reproducibility. In the experiments reported here, reproducibility was not a major problem, although it is likely that x rays produced by energetic electrons striking the drift tube walls produced sufficient free electrons to initiate the breakdown process.

Future experiments are planned to extend the range of data obtained to even higher microwave power densities and shorter pulse durations. In addition, the propagation of high-power microwave pulses through preformed plasmas is also under study.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge useful discussions with Dr. C. D. Striffler and H. Rappaport. We are also grateful for the loan of several pieces of equipment by Harry Diamond Laboratories. This work was supported by the Air Force Office of Scientific Research.

[1] E. K. Smith, Radio Sci. **16**, 1455 (1982).
[2] H. J. Liebe, IEEE Trans. Antennas Propag. **AP-31**, 102 (1983).
[3] A. D. MacDonald, *Microwave Breakdown in Gases* (Wiley, New York, 1966), p. 160.
[4] H. W. Bandel and A. D. MacDonald, J. Appl. Phys. **41**, 2903 (1970).
[5] W. E. Scharfman, W. C. Taylor, and T. Morita, IEEE Trans. Antennas Propag. **12**, 709 (1964).
[6] D. J. Rose and S. C. Brown, J. Appl. Phys. **28**, 561 (1957).
[7] G. Bekefi, *Principles of Laser Plasmas* (Wiley, New York, 1976), p. 457.
[8] Y. A. Lupan, Sov. Phys. Tech. Phys. **21**, 1367 (1976).
[9] S. M. Flatte, Proc. IEEE **71**, 1267 (1983).
[10] P. Felsenthal and J. M. Proud, Phys. Rev. **139**, A1796 (1965).
[11] W. Woo and J. S. DeGroot, Phys. Fluids **27**, 475 (1984).
[12] J. H. Yee, R. A. Alvarez, D. J. Mayhall, D. P. Byrne, and J. Degroot, Phys. Fluids **29**, 1238 (1986).
[13] A. W. Ali and T. Coffey, Naval Research Laboratory Memorandum Report No. 4320, 1980 (unpublished).
[14] W. M. Bollen, C. L. Yee, A. W. Ali, M. J. Nagurney, and M. E. Read, J. Appl. Phys. **54**, 101 (1983).
[15] L. Gould and L. W. Roberts, J. Appl. Phys. **27**, 1162 (1956).
[16] S. J. Tetenbaum, A. D. MacDonald, and H. W. Bandel, J. Appl. Phys. **42**, 5871 (1971).
[17] W. T. Armstrong, R. A. Roussel-Dupre, R. Karl, M. I. Buchwald, and G. Graham, Bull. Am. Phys. Soc. **31**, 1615 (1986).
[18] H. Rappaport, P. E. Latham, and C. D. Striffler, Bull. Am. Phys. Soc. **31**, 1553 (1986).