Shielded-source, short-pulse microwave propagation experiments

W. W. Destler, Z. Segalov, and J. Rodgers
Electrical Engineering Department, University of Maryland, College Park, Maryland 20742

(Received 13 February 1989; accepted for publication 18 April 1989)

The propagation of short-pulse, high-power microwaves through a neutral gas has been studied and breakdown limits determined in an experimental configuration in which the neutral gas test cell was carefully shielded from x-rays emanating from the high-power microwave tube. In this manner the possible x-ray generation of free electrons in the test cell was minimized. Results are compared with previous experiments in which the test cell was not shielded from the source.

Renewed interest in the propagation of high-power microwave pulses in the atmosphere[1–5] has resulted from the availability of very high-power microwave sources with pulse durations in the range 2–1000 ns.[6] It has been suggested that extremely high levels of microwave power can be propagated in the atmosphere if the microwave pulse duration is significantly shorter than the time required to build up electron densities sufficient to absorb or reflect significant microwave energy.

In previous work,[7] our group has reported studies of the propagation of high-power (50–300 kW/cm^2), short-pulse (2–35 ns) microwaves through an air-filled test cell. In these experiments, microwaves from a high-power large orbit gyrotron were focused into a test cell using a large diameter parabolic reflector, and microwave breakdown thresholds were determined over a wide range of test cell pressure and microwave power density and pulse duration. These free-space microwave breakdown thresholds were found to be comparable to previous data obtained on breakdown limits in waveguides, and shorter pulse durations did allow higher microwave power densities to propagate without breakdown, as expected.

It has been suggested,[8] however, that x radiation produced by the energetic electrons in the large orbit gyrotron could be responsible for generating a number of free electrons in the test cell, and that breakdown might therefore have been observed at artificially low values of microwave power density. In the experiments reported herein, the test cell was carefully screened from the large orbit gyrotron x radiation by a concrete and lead shield wall, and breakdown limits were determined in the manner reported previously. Thus, a ready comparison between breakdown limits with and without source x-ray shielding is now possible.

In this communication, related theoretical considerations are discussed, the experiments conducted are detailed, and results are compared with previously obtained unshielded source breakdown limits.

The theory of microwave breakdown of a neutral media is treated extensively in early work by MacDonald.[9] This treatment assumes that breakdown occurs when the electric field of the microwaves accelerates any free electrons in the media to energies sufficient to cause ionizing collisions with neutrals. The resulting production of additional electrons drives an avalanche process that results in a rapid rise in the plasma density and eventual microwave absorption or reflection. The continuity equation for electrons in the media is written

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

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. Usually the diffusion term is approximated as $\nabla^2(Dn) \cong n(-D/\Lambda^2)$, where Λ is the characteristic diffusion length and is dependent upon the particular system geometry. Under this approximation, the continuity equation yields

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

where ν is a net rate for electron production. A reasonable estimate of the time required to reach breakdown is obtained if it is assumed that breakdown occurs when the plasma density reaches the critical plasma density for wave propagation

$$n_p = 10^{13}/\lambda^2 \ (\mathrm{cm}^{-3}). \tag{3}$$

The pulse duration τ for breakdown to occur is then given by

$$n_p = n_0 e^{\nu\tau}. \tag{4}$$

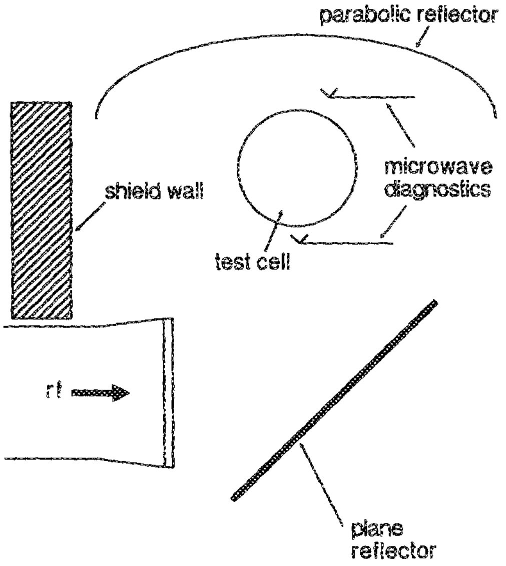

FIG. 1. Experimental configuration used for shielded-source microwave propagation experiments.

Although the initial free-electron density is not known to any degree of accuracy in most experiments, the exponential nature of the rise in electron density with time tends to minimize the effects of errors in the number assumed for n_0. Nevertheless, this effect can be significant. For 3-cm microwaves, for example, the difference between $n_0 = 1$ and $n_0 = 1000\ \text{cm}^{-3}$ represents about a 25% change in the breakdown pulse duration assuming other quantities remain fixed. Of course, if a media can be found in which $n_0 = 0$, breakdown will not occur for any pulse length unless the wave electric field is large enough to directly strip an electron from a neutral.

High-power microwave pulses used for the propagation experiments were generated by a large-orbit gyrotron operating at 10 GHz, as reported previously.[7] This device produces high-power microwave radition (100–500 MW) by the resonant interaction of a rotating electron beam with the modes of a multiresonator magnetron circuit. The experimental configuration used for the propagation experiments is shown in Fig. 1. Microwaves from the large-orbit gyrotron are reflected 90° by a plane reflector toward a 150-cm-diam parabolic reflector. The parabolic reflector serves to focus the microwaves into the test cell. The test cell, a 30-cm-diam cylindrical acrylic vacuum chamber, is fitted with a high accuracy vacuum gauge and a calibrated leak valve that allowed maintenance of ambient pressures from atmosphere down to 0.1 Torr. Measurements of the microwave power density along the disk axis (Fig. 2) and across a cell diameter (Fig. 3) indicate that a reasonable focus was achieved away from the test cell walls (surface breakdown on the test cell walls must be avoided if true media breakdown limits are to be established).

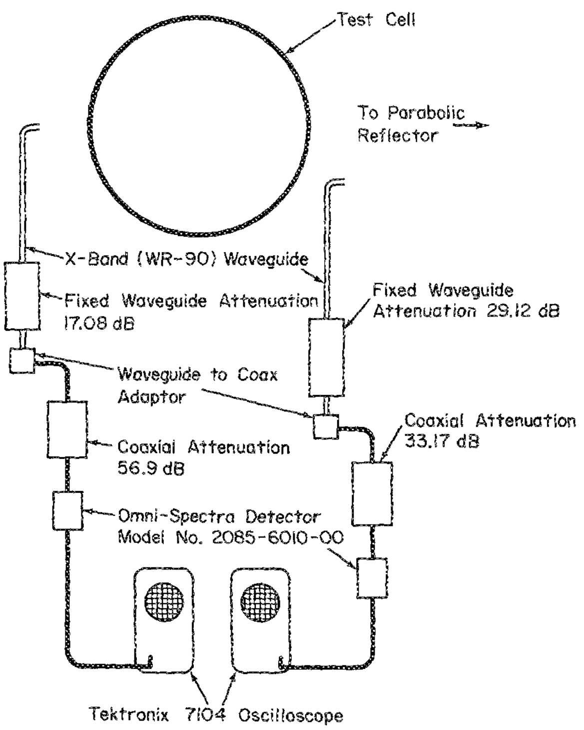

FIG. 2. Schematic of microwave diagnostic setup used in the propagation experiments.

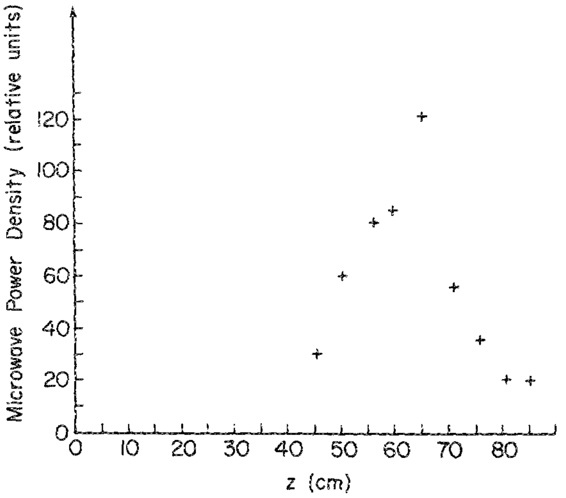

FIG. 3. Microwave power density vs distance along the axis of the parabolic reflector.

The shield wall between the large-orbit gyrotron and the test cell was constructed of 20-cm-thick high-density concrete block augmented by 1 cm of lead sheet. Measurements of the x radiation observed at the test cell indicate that the shield wall reduced x radiation by more than two orders of magnitude, with typical TLD detector dosage recordings of 50 mR/shot observed without the shield wall and 0.5 MR/shot after the shield wall was constructed. Because of reflections, it was not possible to completely eliminate all x radiation from the test cell area.

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. 4. Microwave signals were passed through calibrated attenuators to calibrated detectors selected for their measured transient response time (rise time ~1 ns). Detector signals were fed directly into Tektronix 7104 oscilloscopes.

In this work, breakdown of the media was said to occur if either visible light from ionization processes was observed in time-integrated photographs of the test cell or if signifi-

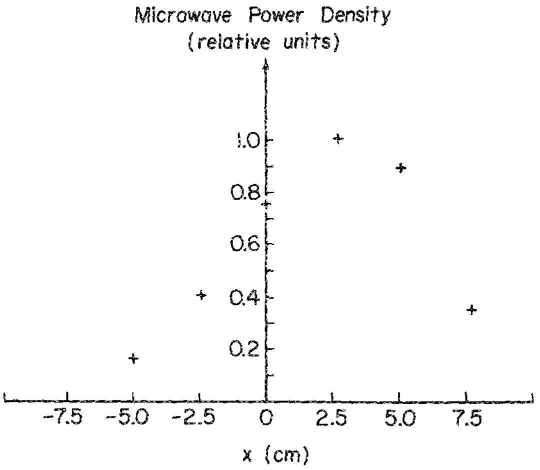

FIG. 4. Microwave power density vs distance across a diameter of the test cell.

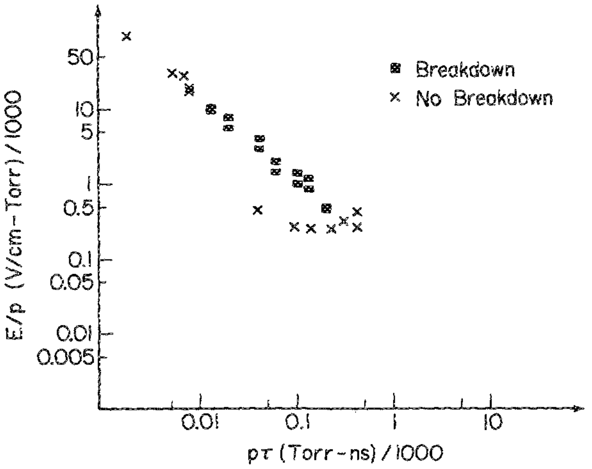

FIG. 5. Microwave propagation data.

cant shortening of the post-focus microwave pulse was observed due to reflection and/or absorption of the microwaves by the breakdown plasma. The criteria for pulse shortening to indicate breakdown was if the transmitted pulse duration was 80% or less of the incident pulse duration. Microwave power density was varied over the range 50–300 kW/cm^3 and pulse duration was varied over the range 3–20 ns. Data for the experiments are plotted in the familiar E/p vs $p\tau$ format in Fig. 5.

From the data shown in Fig. 4 and previously reported data,[7] it appears that a significant reduction in background radiation does increase the wave electric field required for breakdown, at least at high (>1000) and low (<10) values of $p\tau$. This increase in the breakdown electric field, about a factor of 2 over the previously reported data, is small but nevertheless large enough to ensure that statistical fluctuations alone cannot account for the increase.

Unfortunately, it is nearly impossible to measure accurately the actual free-electron density in the test cell at the time these measurements were made, due primarily to the unavailability of diagnostics sensitive enough to yield quantitative estimates of such low electron densities. Even a theoretical estimate would require a very careful measurement of the x-ray energy spectrum and information on x-ray induced ionization cross sections over the entire spectrum. Nevertheless, the data and the theoretical discussion suggest that breakdown thresholds as reported here and in the previous report[7] are reasonably reliable as long as at least a few free electrons are present in the media. Natural radioactivity and cosmic radiation are probably sufficient to ensure that this is the case.

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

[1] W. Woo and J. S. DeGroot, Phys. Fluids 27, 475 (1984).
[2] J. H. Yee, R. A. Alvarez, D. J. Mayhall, D. P. Byrne, and J. Degroot, Phys. Fluids 29, 1238 (1986).
[3] A. W. Ali and T. Coffey, Naval Research Laboratory Memorandum Report No. 4320, 1980 (unpublished).
[4] W. M. Bollen, C. L. Yee, A. W. Ali, and M. J. Nagurney, and M. E. Read, J. Appl. Phys. 54, 101 (1983).
[5] S. M. Flatte, Proc. IEEE 71, 1267 (1983).
[6] V. L. Granatstein and I. Alexeff, Eds., *High Power Microwave Sources* (Artech House, MA 1987), and references therein.
[7] C. A. Sullivan, W. W. Destler, J. Rodgers, and Z. Segalov, J. Appl. Phys. 63, 5228 (1988).
[8] W. M. Bollen (private communication).
[9] A. D. MacDonald, *Microwave Breakdown in Gases* (Wiley, New York, 1966), p. 160.

Propagation of electromagnetic waves of crossroads with a reflector inside a tunnel

Yasushi Murakami and Jiro Chiba
Department of Electrical Engineering, Tohoku University, Sendai 980, Japan

(Received 19 December 1988; accepted for publication 13 March 1989)

We analyzed the wave propagation characteristics of the crossroad inside a tunnel, using the boundary-element method. To simplify, the tunnel structure is assumed to be two-dimensional and the side walls to be lossy dielectrics. We could improve the radio communication characteristics between two cross tunnels by a tetragonal reflector placed at the center of the crossroad. The diagonal length of the proper reflector is about 10%–20% of the tunnel width.

At present, various studies have been conducted on the wave propagation characteristics in an effort to secure safety and improve communication among moving bodies inside tunnels, underpasses, and galleries.[1–4] Little attention, however, has been paid to the discontinuity problem of the tunnel with lossy walls. Uchida, Matsunaga, and Noda have studied the discontinuity of a T junction in the tunnel.[5] They assumed the tunnel structure to be two-dimensional and the