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KINETIC AND FLUID THEORY OF MICROWAVE BREAKDOWN IN AIR

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Introduction

Below microwave frequencies of 10 GHz, the transmission properties of air to high-power microwave (HPM) radiation in the non-relativistic regime are defined by the details of two basic processes; namely, air breakdown and tail erosion. It is important to note that the propagation of short pulse (< 100 ns), high-power microwaves through air is intrinsically a non-equilibrium phenomenon. The time scales over which electron swarms form and absorb energy from HPM pulses are such that thermodynamic equilibrium is never established and electron velocity distribution functions can, therefore, depart significantly from Maxwellian. Even at low altitudes where collision times for angular redistribution of electrons and for energy loss resulting from inelastic processes are much shorter than pulse lengths, the time scales for equilibration to the neutral-background thermal pool are long and the electrons act as an independent species driven by a radiation field which itself is divorced from the thermodynamic properties of the plasma and neutral gases. Departures of the electron velocity distribution functions from Maxwellian are further enhanced by the fact that cross-sections for electron-air interactions vary by orders of magnitude over the energy range of interest, making part of the electron population collision-dominated and part collisionless. All of these effects clearly point to the necessity for a kinetic treatment of the electron swarm. This fact has been noted extensively in the literature for theoretical treatments of air breakdown (cf., [1],[2]) as well as for the modeling of steady-state swarm experiments (cf.,[3],[4]).

In an effort to quantify the important non-equilibrium effects for this problem, we have developed time-dependent fluid and kinetic treatments of electron transport in air in the presence of a propagating microwave pulse. In both cases the HPM pulses are assumed to be of short enough duration so that electron spatial diffusion can be neglected. In addition, we limit our calculations to the non-relativistic regime where effects due to the ponderomotive force are negligible.

Fluid Treatment

The fluid analysis is simply a special case of the more general kinetic treatment in which the electron velocity distribution function is assumed to be a drifting Maxwellian defined in terms of three parameters; namely, density (n_e), mean velocity (v_0) and temperature (T_e). By taking appropriate moments of the Boltzmann equation one obtains a set of equations that describe the temporal evolution of the electron gas in the presence of a HPM field. Neglecting electron spatial diffusion over the short time scales of interest and the ponderomotive force and assuming that the incident microwave pulse is a plane-parallel wave, these equations can be written:

$$dn_e/dt = R_c(v_0,T_e)\, n_e \qquad (1)$$

$$dv_0/dt = -eE/m_e - (R_m(v_0,T_e)+R_c(v_0,T_e))\,v_0 \qquad (2)$$

$$dT_e/dt = -(2\,R_e(v_0,T_e)/3 + R_c(v_0,T_e))\,T_e \qquad (3)$$

where t represents time, e is the absolute magnitude of the electron charge, m_e is the electron mass and R_c, R_m and R_e are collision rates obtained by taking the first three moments (continuity, momentum conservation, energy conservation) respectively of the Boltzmann collision integral. The collision processes incorporated into our calculations include elastic, inelastic and ionizing collisions of electrons with both N_2 and O_2.

Equations (1) - (3) are solved in conjunction with Maxwell's equations to obtain a self-consistent result for the temporal evolution of the electromagnetic pulse as it propagates through the atmosphere. The appropriate Maxwell's equations reduce to a single equation for the electric field E given by:

$$d^2E/dt^2 - c^2d^2E/dz^2 = -4\pi\, dj/dt \qquad (4)$$

where c is the speed of light, j the electron current ($= -n_e e v_0$) and z is the direction of propagation of the HPM pulse. The results of our fluid calculations are compared with breakdown measurements in Section IV.

Kinetic Treatment

In our kinetic treatment, the electron distribution function is expanded in terms of Legendre polynomials ($P_l^0(\mu)$) in the frame of reference moving with the average velocity of the electrons with the expansion carried out to four terms i.e.,

$$f(V,\mu) = \sum_l f^{(l)}(V)\, P_l^0(\mu) \qquad (5)$$

where $V (= |\mathbf{v} - \mathbf{v}_0|)$ is the electron speed and μ the cosine of the angle between the electric field and the velocity vector, both measured in the drift frame of the electrons. Substituting equation (5) into the Boltzmann equation and dotting the result with the first four Legendre polynomials yields a set of coupled equations for the $f^{(l)}$, $l = 0-3$, given by:

$$\partial f^{(l)}/\partial t - (eE/m_e + dv_0/dt)\,[(l/(2l-1))\,(d/dV - (l-1)/V)\, f^{(l-1)} + ((l+1)/(2l+3))\,(d/dV + (l+2)/V)\, f^{(l+1)}] = (l + 1/2) \int d\mu\, P_l^0(\mu)\,(S_{in} - S_{out}) \qquad (6)$$

with

$$dv_0/dt = -eE/m_e + \int d\mu \int dV\, V^3 \mu\, (S_{in} - S_{out})/n_e \qquad (7)$$

where $S_{in} - S_{out}$ represents the Boltzmann collision integral which includes elastic, inelastic and ionization terms. A full microscopic treatment of elastic and inelastic processes appropriate to electron-air interactions is included in our analysis and the cross-sections of Phelps (1986) are used in both fluid and kinetic treatments.

Equations (4) - (7) are solved simultaneously to yield a self-consistent result for the temporal evolution of the electron distribution function and the HPM pulse. Preliminary results of our kinetic calculations are summarized in the following section.

Results

A. Fluid Calculations

The accuracy of our fluid code was tested by comparing breakdown thresholds against the experimental results of Felsenthal and Proud (5) and those of Byrne (6). Breakdown can be defined as the time for the electron swarm to avalanche in the presence of a given electric field to a specified density. In our fluid calculations we obtain the time τ that it takes the electron density to reach a value 10^8 times larger than its initial value (a formulation adopted by Felsenthal and Proud) from the avalanche rate calculated for a specified value of electric field strength to neutral density (E/N). In this way a plot of E/P vs Pτ can be generated for comparison with experimental results. Figure 1 shows such a plot comparing fluid calculations with the measured results of (5). The agreement with data is within 30% in the range $2 \times 10^{-7} < P\tau < 2 \times 10^{-5}$ and $3 \times 10^{-9} < P\tau < 7 \times 10^{-9}$. Outside this range, the agreement is poor. At high pressure we see the effect of the high energy tail, as the fluid calculations can understimate the avalanche rates by orders of magnitude. At low

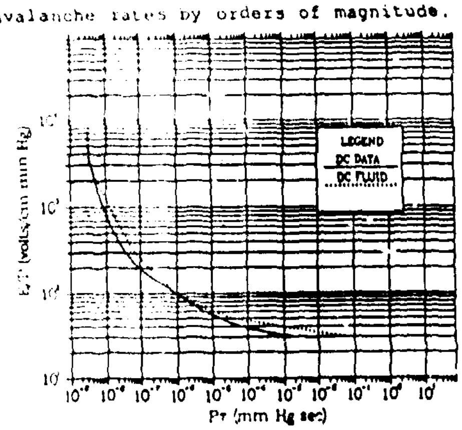


Figure 1

pressure we find the fluid calculations underestimate these rates by factors of two, a result that could be explained in terms of non-equilibrium effects. An additional characteristic of breakdown that is predicted by theory but as yet not verified by experiment is the turning back of the E/P vs. Pτ curve at Pτ = 3×10^{-9}. This effect is associated with the fact that the ionization rate has a peak at electron energies of 300 ev. Above this energy the ionization rate falls and breakdown requires a longer time to achieve critical density. Our calculations for dc pulses were stopped when Pτ reached a value of 4×10^{-9}. Beyond this point the bulk of the electrons run away and a relativistic treatment is needed. We are in the process of developing a code to address this regime. We expect, however, that the curve will turn back up rapidly because the ionization rate flattens out at high electron energies.

For microwave pulses, an oscillating electric field with a square envelope was used in equation (2). Our results for breakdown thresholds are plotted in terms of an effective breakdown field defined as $E_e = E_{rms}/(1 + \omega^2/\nu^2)^{1/2}$ where ω is the central frequency of the microwave pulse and ν is an effective collision frequency defined to be 5.3×10^9 P where P is given in torr and the result is in units of sec^{-1}. Results of our fluid calculations are compared against the recent S-band measurements of [6] shown in Figure 2. Again the agreement is excellent for intermediate values of Pτ while strong

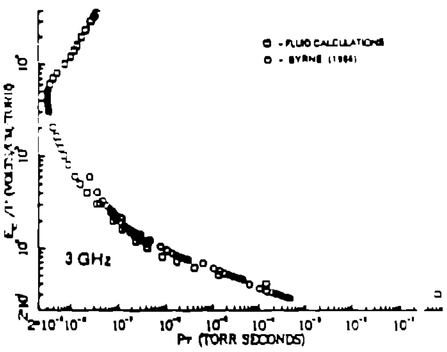


Figure 2

discrepancies exist at low and high pressures as in the dc calculations. Because run-away occurs at much higher effective field strengths than in the dc case, the turning over of the curve can be carried out farther on this plot. For the 3 GHz case studied, the curve turns around at Pτ = 3×10^{-9} and proceeds to higher values while at the same time turning up to higher thresholds for breakdown as expected from the discussion of the dc results.

To illustrate the important characteristics of tail erosion we have performed fluid calculations for the following heuristic example. A triangular shaped pulse 2 ns long with a 0.6 ns rise time and central frequency of 35 GHz was injected at 40 km altitude and allowed to propagate to the ground. The peak field strength was chosen to be 3 MV/M. The resultant pulses at various altitudes are shown in Figure 3. As expected the tail of the pulse shows maximum erosion at an altitude of 28 km where the pulse central frequency is approximately equal to the collision rate defined at the average energies achieved by the swarm electrons. Tail erosion occurs over a range approximately equal to an atmospheric scale height (7 km) while the maximum electron densities achieved at the various altitudes never exceeded 10^8 cm^{-3}, well short of the critical density (= 1.5×10^{13} cm^{-3}).

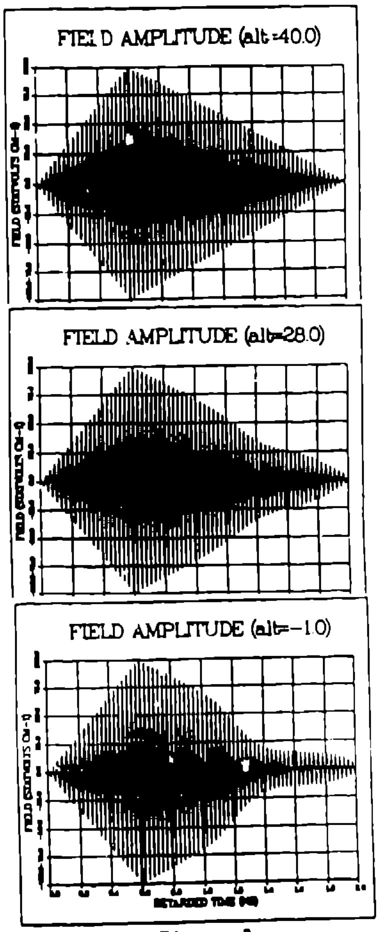
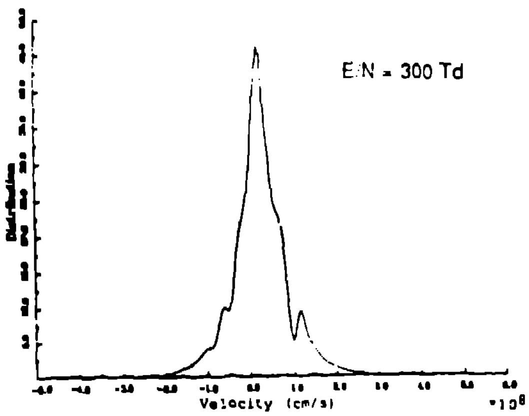


Figure 3

B. Kinetic Calculations

The greater part of our kinetic calculations are in progress and only preliminary results are presented here. In Figure 5, a plot of the steady-state electron velocity distribution function is presented for a value of E/N = 300 Td. The distribution function is clearly non-Maxwellian and two important features are apparent: 1) A high-energy tail that is overpopulated relative to a Maxwellian exists for electron energies above 10 ev, and 2) A bump-on-tail exists at electron energies of approximately 3 - 8 ev. The latter feature is associated with the strong N_2 vibrational transitions that peak at an energy of 2.3 ev. These inelastic collisions deplete the electron population at energies near the peak of the transition rate while the electric field accelerates electrons beyond the peak; thereby, populating the energy range just beyond the peak. These two features of electron transport in air illustrate quite clearly the importance of kinetic effects in defining the swarm characteristics that govern HPM propagation through the atmosphere.



Conclusions

Our efforts in the area of HPM propagation have been founded on a detailed analysis of the microphysics of air breakdown and tail erosion. Preliminary results suggest that kinetic effects are important in defining the optical and RF emissions observed during breakdown and in obtaining breakdown thresholds at low and high pressures. We have developed a unique approach to characterizing high-power microwave propagation by means of the E/P vs. Pτ curve and identified a new regime on this curve that needs to be verified experimentally. We are in the process of incorporating the angular dependence of electron-neutral collisions into our calculations. In addition, a technique for including spatial diffusion is being developed so that detailed comparisons with swarm measurements can be made. The results of our theoretical and experimental program will become available in the near future.

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