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MICROWAVE CAVITY DIAGNOSTICS OF MICROWAVE BREAKDOWN PLASMAS

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By: Donald J. Eckstrom and Mark S. Williams

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LOS ALAMOS NATIONAL LABORATORY
P.O. Box 990
Los Alamos, NM 87545

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Attention: Dr. W. T. Armstrong

Approved by:

D. C. Lorents, Laboratory Director
Chemical Physics Laboratory

G. R. Abrahamson
Senior Vice President
Sciences Group

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ABSTRACT

We have performed microwave cavity perturbation measurements in the LLNL AIM facility using a 329-MHz cavity that allow us to examine in detail the plasma formation and decay processes for electron densities between approximately 10^5 and $10^7/\text{cm}^3$. We believe these to be the lowest density plasmas ever studied in microwave breakdown experiments, and as such they allow us to determine the power and energy required to produce plasmas suitable for HF radar reflection as well as the effective lifetimes of these plasmas before re-ionization is required. Analyses of these results leads to the following conclusions.

- For microwave breakdown pulses varying from 0.6 to 2.4 μs , the threshold power required to produce measurable plasmas is 30 to 12 MW/m^2 at 0.01 torr, decreasing to 3.5 to 1.8 MW/m^2 at 1 to 3 torr, and then increasing to 5 to 3.5 MW/m^2 at 30 torr. The threshold power in each case decreases with increasing pulse length, but the required pulse energy *increases* with decreasing power or increasing pulse length. This observation is consistent with previous measurements of the energy required to produce full microwave breakdown.
- The effective electron density decay rates are approximately $10^2/\text{s}$ for 0.1 to 1 torr, after which they increase linearly with pressure. Thus, the useful plasma lifetimes are in the range of 20 to 40 ms at the lower pressures and decrease to about 1 ms at 30 torr. The decays appear to be due to some combination of diffusion and recombination for pressures below 1 torr, and to a balance between attachment and detachment at higher pressures. With the assumption that diffusion is not important except at the very lowest pressures, these decay rates and lifetimes should be comparable to those that would exist for artificially ionized regions in the upper atmosphere.
- The collision frequencies measured at pressures of 1 torr and above correspond to electron temperatures of 800 K or less. In fact, the inferred temperatures for $p > 3$ torr are below room temperature. This may be due to a contribution to the measured conductivity by negative ions.

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INTRODUCTION

The Artificial Ionospheric Mirror (AIM) Program is an analytical and experimental study of plasmas produced by microwave breakdown in low pressure air to determine the feasibility of producing plasma layers in the upper atmosphere suitable for reflecting radio-frequency waves for over-the-horizon radar and for communications applications. SRI International has been supporting the research program at the Los Alamos and Livermore National Laboratories (LANL and LLNL) by performing microwave diagnostics on plasmas produced in the AIM facility at LLNL.

This is the third series of such experiments we have participated in. In the first two experiments, called the AIM II and AIM III campaigns, we made 10-GHz microwave interferometer measurements on the relatively high density plasmas ($5 \times 10^{10} \leq N_e \leq 2 \times 10^{11}/\text{cm}^3$) produced when the high power S-band microwave pump source (2.856 GHz) was focused onto a reflecting plate set at 45° , which caused breakdown at the self-interference layer parallel to the plate. Our results for the AIM II tests, which consisted of single breakdown pulses, were reported in Ref. [SE89]. Results for the AIM III tests, which included repetitive bursts of pulses for the study of plasma maintenance, were similar. We also measured optical emission spectra of the breakdown plasmas over the spectral range from 200 to 700 nm in the AIM II series [Ec88].

In the present program, we used the microwave cavity perturbation technique with a cavity resonant at 329 MHz to measure electron densities of $2 \times 10^5 \leq n_e \leq 1 \times 10^7/\text{cm}^3$ for plasmas formed at the focus of the S-band beam without the reflecting plate. The motivation for these measurements was threefold: (a) to study plasma decay rates in the late afterglow, (b) to study energy versus power requirements for producing subcritical plasma densities, and (c) to measure plasma density growth rates while the pump beam was on.

These experiments were uniquely capable of studying plasma decay rates for two reasons. First, in the previous AIM experiments, the sensitivity of the 10-GHz interferometer was limited to $n_e > 1 \times 10^{10}/\text{cm}^3$, whereas a plasma layer is still capable of reflecting HF radars at densities below $10^7/\text{cm}^3$. The mechanism of plasma decay, and therefore the decay rate, can change markedly over such a wide range of densities, and so a simple extrapolation of the higher density results is not reliable. Second, in the previous

experiments the plasma was close to the surface of the reflecting plate, so that the plasma decay was influenced by diffusion to the surface. Thus, those results may not be applicable to free-space plasmas even at high densities. By contrast, the microwave cavity used in the present experiments was very large (see below), so that diffusion should not be important except possibly at the lowest pressures. Furthermore, we measure electron densities of a magnitude directly applicable to HF radar frequencies so that no extrapolation is necessary.

The second objective of these experiments was motivated by a suggestion by Papadopolous [Pa88] that the energy of the pump beam required to produce the lower density plasmas ($n_e \sim 10^7/\text{cm}^3$) would be less for lower power, long pulses than for short, high power pulses. This suggestion conflicts with the results of previous AIM studies of the 2.856-GHz energy required to produce full breakdown plasmas (i.e., $n_e \geq n_{\text{crit}}$) [Ar88], but no evaluation could be made about lower density plasmas because there has been no attempt to diagnose such low densities until now.

The third objective was viewed as a possible side feature of the measurements that might provide some details of the electron avalanche process. However, measurement of the electron density growth rate during the pump pulse proved impossible for two reasons. First, the response time of the cavity was approximately $1 \mu\text{s}$, which is comparable to the duration of the pump pulses. Second, 2.856-GHz radiation leaked through the 329-MHz bandpass filters used for the microwave cavity perturbation measurement, and the resulting "noise" obscured the signals, precluding any data evaluation during the pump pulse. Thus, we will not address this objective further.

EXPERIMENTAL DETAILS

THE LLNL AIM FACILITY

The AIM test facility is shown schematically in Figure 1. The primary test chamber is a cylindrical tank 103 cm in diameter by 190 cm long; a secondary cylindrical tank 91 cm in diameter by 183 cm long, which is fitted with a 2000 L/s turbopump, can be rolled back to provide access to the interior of the chamber. The primary chamber is lined with Emerson and Cummings SPY-8 microwave absorbing foam (8 inches thick) to minimize reflection and scattering of the pump beam, while the secondary tank is lined with 4-inch thick SPY-4. The 2.856-GHz pump power was provided by a klystron source of 20 MW peak power and 2.4 μ s maximum pulse length. Power was transferred from the klystron to the chamber in a pressurized waveguide, then through a rectangular to circular transition, and finally through a conical expansion into the chamber. The beam was refocused by a pair of hyperbolic lenses designed to produce a beam waist 75 to 80 cm beyond the second lens. The intensity distribution has been mapped by LLNL personnel [Si89] and is shown in Figure 2. The beam waist actually occurs at 55 cm. The structure in the intensity distribution is caused by weak reflections within the chamber. The reflection pattern, and consequently the structure, may be changed by the installation of the microwave cavity.

The tank was pumped for a minimum of three days before measurements were performed, at which time the base pressure was 2×10^{-5} torr. Experiments were performed at pressures of 0.01, 0.03, 0.1, 0.3, 1, 3, 10, and 30 torr by filling the tank with dry compressed air. After a set of measurements had been made at a given pressure, the tank was evacuated to $(1-10) \times 10^{-4}$ torr before it was refilled to the next test pressure, except for the 30-torr measurements, in which case the tank was filled directly following the 10-torr experiments without intermediate evacuation. Each set of measurements required about 45 minutes, during which the pressure rose by approximately 1 mtorr, presumably because of outgassing. The temperature in the chamber varied from 15-21°C over the course of the experiments.

During several preliminary series of experiments, preionization in the test chamber was provided by placing a 5-mC source of Co^{60} in a collimator on the top of the test chamber directly above the microwave cavity. However, in the final series, for which

Figure 1. Schematic of LLNL AIM facility with 329-MHz microwave cavity.

Figure 2. Pump beam intensity distribution and cavity wall locations.
Field measurements provided by G. Sieger of LLNL.

results will be presented here, preionization was provided by a pulsed x-ray source consisting of a Marx-generated electron beam of 200-kV energy incident on a tantalum anode. This source produced 13 $\mu\text{R}/\text{pulse}$, which is estimated to generate 10 electrons/ cm^3 when the air pressure in the chamber is 3 torr [Al89]. Scaling linearly with pressure gives over 600 electrons in the active volume of the cavity even at the lowest test pressure of 0.01 torr.

MICROWAVE CAVITY DIAGNOSTICS

The microwave cavity perturbation technique is a well established method for measuring electron density decay histories in various types of plasmas, including those generated by microwave breakdowns. However, in most cases the method is applied only to collisionless plasmas, in which case the resonant frequency of the cavity is shifted by the plasma but the Q of the resonance is assumed not to change. We have performed an extensive set of measurements of plasmas generated in air by a pulsed electron beam [SDE87], in which we simultaneously determined the time histories of the shift of resonant frequency (Δf) and of Q (ΔQ), and from the combination we were able to determine both electron density and collision frequency histories over a wide pressure range. Those measurements required a large number of repetitive shots to acquire the complete time histories of both Δf and ΔQ , so we were led to develop the microwave cavity reflection interferometer, which allows determination of the complete time histories of both parameters in a single shot [EWD87]. That technique was used for these measurements.

The frequency of the microwave cavity was chosen to provide sensitivity for electron densities from 10^6 to $10^8/\text{cm}^3$, which requires microwave frequencies on the order of 100 MHz. We chose an operating frequency of 329 MHz because the resulting cavity, which has a diameter of 71 cm, just fits inside the AIM test chamber without modifying the absorbing foam lining. The cavity was installed in the tank as shown schematically in Figure 1, so that it was centered approximately at the waist of the focused S-band pump beam. Holes 23 cm in diameter centered on the axis of the cavity endwalls allowed the strongest part of the pump beam to pass through the cavity with minimum perturbation, although the wings of the beam were occulted by the cavity as shown in Figure 2. The solid part of the front of the cavity was covered with the SPY-8 microwave absorbing foam to minimize reflections and scattering of that radiation. The cavity length of 46 cm was chosen to provide a minimum ratio of two for the length of the cavity to the diameter of the endwall holes in order to minimize the distortion of the TM_{010} mode fields in the cavity. Nevertheless, the fields did extend beyond the endwalls, as could be readily detected by

monitoring the resonant frequency and Q as objects were brought close to the cavity. No correction for this field distortion has been made.

The microwave cavity reflection interferometer is essentially a Mach-Zehnder interferometer configuration, as shown schematically in Ref. [EWD87], consisting of the active leg containing the cavity and a reference leg containing a phase shifter and an attenuator. We found that those two components in the reference leg could be omitted if we were willing to operate at whatever relative phase shift happened to occur. The resulting layout is shown schematically in Figure 3.

The two bandpass filters shown were essential to protect the detectors from the high power pump beam. At one point, we operated without them and consequently burned out both HP 423B detectors in a single pump pulse. We were thus forced to complete the measurements using one borrowed HP 423B detector and a second HP detector of unknown model and vintage. The detectors were calibrated *in situ* using an HP 432A power meter.

The time histories of the detector signals representing reflected power and interference power were recorded using a Tektronics Model 2430 dual beam digital oscilloscope and were subsequently transferred to a Compaq computer for analysis using the NPLAY program provided to us by Dr. F. Chambers of LLNL. The microwave source was an HP8340B synthesized sweep oscillator furnished by LLNL.

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Figure 3. Experimental setup for microwave cavity reflection interferometer.

I = Isolator; DC = Directional Coupler; D = Detector; SW = Switch;
F = Bandpass Filter.

DATA ANALYSIS

The complex electrical conductivity of a plasma may be expressed as

$$\hat{\sigma} = -\frac{4\pi}{3} \frac{n_e e^2}{m_e} \int_0^{\infty} \frac{1}{v_e + j\omega} \frac{df_0(v)}{dv} v^3 dv \quad (1)$$

where e and m_e are the charge and mass of the electron, respectively, and n_e is the electron density. This expression can be evaluated for arbitrary microwave frequency, ω , and variation of v_e , the electron collision frequency, with v if the electron velocity distribution $f_0(v)$ is known. Usually, the distribution is assumed to be Maxwellian, in which case the real and imaginary conductivities can be calculated as a function of electron temperature, T_e , for arbitrary ω and gas pressure. If one further assumes that v_e is a constant, the conductivity can be written simply as

$$\hat{\sigma} = \sigma_r + j\sigma_i = \frac{\epsilon_0 \omega_p^2}{(v_e + j\omega)} \quad (2)$$

or

$$\sigma_r = \frac{\epsilon_0 \omega_p^2 v_e}{(\omega^2 + v_e^2)} \quad (3)$$

and

$$\sigma_i = \frac{-\epsilon_0 \omega_p^2 \omega}{(\omega^2 + v_e^2)} \quad (4)$$

where $\omega_p^2 = \frac{e^2 n_e}{\epsilon_0 m_e}$ is the square of the electron plasma frequency, which is a function of the plasma density, n_e , and v_e is now the effective electron collision frequency, which is a function of electron temperature. ϵ_0 is the permittivity of free space [$\epsilon_0 = (4\pi)^{-1}$ in cgs units].

The time histories of the electron density, n_e , and the collision frequency, v_e , can be determined from equations (3) and (4) if the time histories of σ_r and σ_i can be measured. The perturbations of the microwave cavity, Q , and frequency are directly related to the real and imaginary conductivities through Slater's cavity perturbation formula [Sl46]

$$\begin{aligned}
\Delta\left(\frac{1}{Q}\right) - 2j\frac{\Delta\omega}{\omega} &= \frac{1}{\epsilon_0\omega} \frac{\int_v \vec{J} \cdot \vec{E} \, dv}{\int_v E_0^2(r) \, dv} \\
&= \frac{1}{\epsilon_0\omega} \frac{\int_v \hat{\sigma}(r) E_0^2(r) \, dv}{\int_v E_0^2(r) \, dv} \\
&= \frac{\hat{\sigma}}{\epsilon_0\omega} \frac{\int_{\text{plasma}} E_0^2(r) \, dv}{\int_{\text{cavity}} E_0^2(r) \, dv} \tag{5}
\end{aligned}$$

Thus, our problem is one of determining the time histories of the cavity frequency and Q . This is accomplished using the microwave cavity reflection interferometer technique [EWD87].

This technique is quite complex and is best understood by consulting Ref. [EWD87] (Appendix A). Briefly, the complex voltage reflection coefficient from the cavity is

$$\Gamma_V = \frac{1 - \alpha - j\alpha a}{1 + \alpha + j\alpha a} = \frac{(1 - \alpha^2 - \alpha^2 a^2) - j2\alpha a}{(1 + \alpha)^2 + \alpha^2 a^2} \tag{6}$$

where $\alpha = Q_{\text{ext}}/Q_u$ and $a = 2(\nu - \nu_0)Q_u/\nu_0$. Q_{ext} and Q_u are the external and unloaded Q of the cavity, respectively, while ν and ν_0 are the probe microwave frequency and the cavity resonance frequency, respectively. The complex voltage reflection coefficient, whose amplitude is the square root of the power reflection coefficient, can also be written

$$\Gamma_V = |\Gamma_V|/\phi \tag{7}$$

The interferometer detectors are calibrated to measure the reflected power, P_1 , and the interference power, P_2 ; the latter parameter is a function of the reflected power and phase angle and the reference power and phase angle as

$$P_2 = P_1 + P_r + 2(P_1 P_r)^{1/2} \cos(\phi_1 - \phi_r) \tag{8}$$

The analysis of the data now proceeds in reverse order. The interferometer measurements yield the reflected power and the cavity phase angle, which are used in

equation (7) to establish the time histories of the real and imaginary components of the voltage reflection coefficient. Those components are then used in equation (6) (after some arithmetic manipulation) to determine the histories of the parameters a and α , which in turn yield the histories of Q_u and v . Q_u and v lead to σ_r and σ_i from equation (5). Finally, we calculate $n_e(t)$ and $v_e(t)$ from equations (3) and (4). An example of a complete set of measured and derived parameters for a single test is shown in Figure 4.

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Figure 4. Typical measured and derived parameters for a cavity perturbation measurement at 3 Torr.

Electron density and collision frequency histories are presented as Shot 162 in Figure 10.

RESULTS AND DISCUSSION

OVERVIEW OF EXPERIMENTS

Our objective of determining the pump beam energy required to produce subcritical plasmas ($n_e \lesssim 10^7/\text{cm}^3$) as a function of pump power led us to perform measurements at five pulse lengths, namely, 0.6, 1.0, 1.4, 1.8, and 2.4 μs , at each of the eight test pressures. We made one or more measurements at each condition, which resulted in a large number of data sets. The results presented are representative of all the data.

At each pressure and pulse length condition, we attempted to raise the pump power gradually until the microwave cavity detected the appearance of a subcritical plasma. However, it should be emphasized that the difference in power level required to produce a low density plasma and a full, overdense plasma ($n_e \geq n_{e\text{crit}} = 1 \times 10^{11}/\text{cm}^3$) was very small, and in some cases we were not able to produce a subcritical plasma at all. Furthermore, even though we waited at least 1 minute between shots, there was often hysteresis in the threshold power level. That is, once breakdown had been achieved at a given power level, the power level on subsequent shots could be lowered below the previous threshold and the plasma would still be produced. Alternately, if a power level was found that produced a subcritical plasma on the first pulse, the plasma density might increase on each subsequent pulse. Apparently some very long-lived species are created, probably negative ions, that facilitate breakdown on subsequent pulses.

The occurrence of a critical plasma could be readily detected by monitoring the detector measuring the reflected power of the pump beam. A critical plasma also created what appeared to be multiple resonances in the microwave cavity reflected power and phase measurements. This behavior suggests that the overdense plasma creates cavity modes with resonant frequencies below that of the empty cavity TM_{010} mode. As the overdense plasma decays, the resonant frequency would sweep across the operating frequency from low to high, creating the observed minimum in reflected power, and would then follow the normal perturbed TM_{010} resonance as it decayed from high back to low frequency. This behavior is quite complex, because in some cases two or three of these "extraneous" apparent resonances were recorded. The simplest explanation would be that the entire core of the plasma on axis was overdense, thus creating a coaxial cylinder cavity [Mo47];

however, the resonances of such a cavity are all at higher frequencies than that of the empty cylindrical cavity. We did observe that a metal post inserted part way into the cavity on the centerline shifted the resonance to lower frequencies, which suggests that a single extraneous resonance might result from an overdense plasma occupying only part of the cavity axis, while a double resonance could result from a plasma that is overdense but nonuniform along the axis, so that it begins as a coaxial cylinder cavity geometry, then decays into a partial post on axis, and finally decays to a perturbed TM_{010} mode of a cylindrical cavity.

In view of these apparent nonuniformities in the plasma density, it is difficult to specify the plasma volume required in the data analysis. We have assumed that the volume is a cylinder of 23 cm diameter, corresponding to the hole diameter in the endwalls. The cavity essentially integrates the total plasma density present, because its sensitivity is nearly uniform over the central 30% of the diameter represented by the open end holes. Then, a knowledge of the actual plasma volume is required to specify the absolute plasma density but not its variation with time. Thus, when the plasma decay is exponential, the decay rate is independent of the assumed plasma volume. In those few cases where the decay appears to be due to recombination, the recombination rate is uncertain by the same amount as the plasma volume.

PLASMA DENSITY DECAYS

In Figures 5 through 12, we present representative electron density histories measured at each of the test pressures. In each figure, two cases are shown; these are chosen insofar as possible so that the first shot is a case where a subcritical plasma was produced and the second shot is for an overdense plasma (as manifested initially by multiple "resonances" in the reflected power history and in these figures by spurious oscillations in n_e versus t at the beginning of the pulse). We also present the electron density histories as semilogarithmic plots and as $1/n_e$ plots, because such plots make the behavior of the decay more apparent; i.e., both electron attachment and diffusion produce exponential decays that appear linear on a semilog plot, while recombination produces a decay that appears linear on a $1/n_e$ plot. (In fact, these statements are only true if the electron temperature is constant. The rates for diffusion, attachment, and recombination all vary with electron temperature.)

The measured electron densities typically range from a maximum of $(2-10) \times 10^7/\text{cm}^3$ to a minimum of $(2-8) \times 10^5/\text{cm}^3$. The total decay times are approximately 20 ms at 10 mtorr pressure, increasing to 40 ms at 100 to 300 mtorr, and then decreasing steadily to approximately 1 ms with pressure increasing to 30 torr. Thus, we have extended the range of decay measurements by 10^5 in electron density and by 10^2 in time compared to our earlier x-band interferometer measurements.

We have examined the semilog and inverse plots in Figures 5 through 12 as well as similar plots for the other shots not presented here in an effort to identify the mechanism of plasma decay. For the 10, 30, and 100 mtorr cases, the decays are not linear on either the semilog or the inverse plots, but the early parts of the decays appear to be more nearly exponential than recombination-like. Both the apparent exponential decay rate and the apparent recombination rate increase with time in the pulse, and both of these increases could be due to a decreasing electron temperature. At 300 mtorr, the early decay appears to be recombination-dominated, going over to exponential at late times. The 1- and 3-torr cases are clearly exponential, and the 10-torr case also favors the exponential form. The 30-torr shots cannot be assigned to either exponential or inverse decay, although exponential behavior is slightly favored. The best fits to exponential decay rates for the early part of the decay at all pressures are presented in Figure 13, while the best fits to a recombination rate constant based on the $1/n_e$ plots are presented in Figure 14.

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Figure 5. Electron density histories at 0.01 torr.

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Figure 6. Electron density histories at 0.03 torr.

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Figure 7. Electron density histories at 0.1 torr.

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Figure 8. Electron density histories at 0.3 torr.

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Figure 9. Electron density and collision frequency histories at 1 torr.

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Figure 10. Electron density and collision frequency histories at 3 torr.

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Figure 11. Electron density and collision frequency histories at 10 torr.

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Figure 12. Electron density and collision frequency histories at 30 torr.

Figure 13. Exponential decay rates for electron density histories.

Figure 14. Recombination decay rates determined from slope of n_e^{-1} plots.

The best fits to exponential decay constants are all larger than $10^2/\text{s}$, and the rates at pressures from 0.3 to 30 torr increase linearly with pressure to a maximum of $\sim 10^4/\text{s}$. We might expect the decays at the lowest pressures to be dominated by ambipolar diffusion of electrons to the walls of the cavity, which has a rate in air of $D_a \equiv 150(1 + T_e/T_i)/p \text{ cm}^2/\text{s}$, where p is given in torr [McD64]. At $p = 0.01 \text{ torr}$, the diffusion coefficient is $1.5 \times 10^4 \text{ cm}^2/\text{s}$ for room-temperature electrons, increasing to $6 \times 10^5 \text{ cm}^2/\text{s}$ for 1-eV electrons. The decay rate due to diffusion in a cylinder is given by $k_{\text{diff}} = D_a(2.405/R)^2$, where 2.405 is the first root of the zero-order Bessel function and R is the radius of the cylinder. For a 35-cm radius, this rate is $0.0046 D_a$, which is $69/\text{s}$ for $T_e = 300 \text{ K}$ and $2.7 \times 10^3/\text{s}$ for $T_e = 11,600 \text{ K}$ (1 eV). These values bracket the observed 0.01-torr decay rate; in fact, the rates match for $T_e \sim 600 \text{ K}$, which indicates that diffusion of warm electrons to the sidewalls could account for the decay. Alternately, accounting for diffusion to the endwalls would increase the calculated decay rate. Now the predicted decay rate due to diffusion decreases linearly with pressure whereas the observed rate is nearly constant for $0.01 \leq p \leq 0.3 \text{ torr}$, which indicates that some other mechanism is contributing to the plasma decay at these low pressures.

Considering next recombination, we see from Figure 14 that the inferred rates at the lower pressures are on the order of $10^{-5} \text{ cm}^3/\text{s}$. Charge transfer and ion clustering rates can be used to calculate that O_2^+ will be the dominant ion during the plasma decay. The electron-ion recombination rate for O_2^+ has a maximum value of $2 \times 10^{-7} \text{ cm}^3/\text{s}$ for room-temperature electrons [MB69] and decreases with increasing T_e . Thus, the observed rates are nearly two orders of magnitude faster than can be readily explained by recombination. We must re-emphasize that the inferred recombination rate is based on the assumption that the plasma uniformly occupies the entire central 23-cm diameter column along the axis of the microwave cavity. If the plasma instead consisted of smaller regions with higher density, more reasonable recombination rates would be inferred.

For pressures of 0.3 torr and above, the measured plasma decay rates increase linearly with pressure. We would expect that three-body electron attachment to O_2 should be the dominant deionization mechanism in this pressure range. However, this process varies quadratically with pressure, with values as shown in Figure 13. The observed rates fall below the attachment rate for 10 and 30 torr. This is a common observation in both microwave breakdown [SML60] and e-beam-ionized [SDE87] plasmas. In fact, the decay rates at 10 and 30 torr are in excellent agreement with our earlier results for e-beam-ionized plasmas, as shown in Figure 13. This lengthening of the decay process beyond the time expected for electron attachment is generally attributed to the countervailing detachment of

electrons from negative ions upon collision of the ions with a metastable excited molecule (such as electronically or vibrationally excited N_2) [cf. VIS84]. Therefore, the plasma decay rate should depend on the initial level of ionization and excitation in the plasma, but such a correlation is not apparent in the results of various experiments. We do measure variations of a factor of 2 in the decay rates at 10 and 30 torr, but there seems to be no correlation with the initial electron density.

We cannot think of an explanation for the apparent linear variation of the decay rate with pressure at the higher pressures. It may be a coincidence of a transition between one decay mechanism dominant at low pressures and another dominant at higher pressures. Coincidentally, we found that our 10-GHz interferometer measurements of AIM plasma decay rates at higher electron densities [SE89] also increased linearly with pressure, although in that case the pressure range was 0.01 to 1 torr and the rate at 1 torr was two orders of magnitude faster than the one measured here.

COLLISION FREQUENCIES

Our measurement of collision frequencies is based on the simultaneous measurement of time dependent shifts of the cavity resonance frequency and cavity Q through the reflection cavity interferometer technique described above. At low pressures, the Q change is so small as to be very difficult to measure; in fact, at any pressure, the accuracy of the measurement depends on the quality of the microwave hardware used in the interferometer circuit and on the accuracy of the detector calibration curves. The imperfections in our setup prevented us from attempting to determine collision frequencies below 1 torr. Representative collision frequencies we determined at 1 torr and above are presented in Figures 9 through 12. Unfortunately, even at these higher pressures, there appears to be a reproducible defect in the measurements that introduces an error into the early part of the collision frequency histories. Thus, we must be satisfied to determine an average collision frequency based on an asymptotic value in the later part of the decay. (Note that the rapidly oscillating values prior to the pulse and late in the decay are numerical instabilities caused by division by zero in the data reduction process.) The collision frequencies determined in this way are plotted in Figure 15 as a function of pressure.

The measured collision frequencies are of interest primarily because they allow inference of an electron temperature. The collision frequencies calculated on the basis of measured momentum transfer cross sections for electrons of temperature 300, 500, and 1,000 K in dry air are plotted in Figure 15 as a function of pressure. The calculated variation with pressure is not linear because the effective collision frequency [It73] changes

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Figure 15. Average collision frequencies determined from ratio of real and imaginary conductivities.

Solid curves are calculated from momentum transfer cross sections for dry air.

from the AC limit ($\omega \gg \nu_e$) at 1 torr to an intermediate case between the AC and DC limits at 30 torr. The measured collision frequency at 1 torr agrees with calculated values around 800 K, and is close to the 300-K value at 3 torr, but the measured values drop progressively below the calculated values for room-temperature electrons with increasing pressure. In fact, the 30-torr value equals the calculated value for 100 K electrons, but there is no rationale for such a cold electron temperature.

We have previously encountered one other situation where the measured collision frequencies were lower than calculated values, namely, for e-beam-excited laboratory air [SDE87]. We attributed that observation to the possibility that the charge carriers dominating the measured conductivity were negative ions rather than electrons. In fact, as shown in Figure 13, the electron attachment rate is faster than the plasma decay rate at 10 and 30 torr, so there can be a significant number of negative ions. However, the sensitivity of the microwave cavity perturbation technique to ions is smaller than its sensitivity to electrons by the ratio m_e/m_i , so there must be $>10^4$ more ions than electrons to cause the same perturbation. This is marginally possible if the initial plasma density equaled the critical density for the 2.856-GHz pump beam ($1 \times 10^{11}/\text{cm}^3$) and if all those electrons attached to create negative ions.

PUMP POWER VERSUS PRESSURE AND PULSE LENGTH

The power threshold for creating a measurable plasma in the cavity is plotted in Figure 16 as a function of pressure and pulse length. The corresponding energies, that is, the threshold power times the pulse length, are presented in Figure 17. The curves through the points are hand-drawn to clarify the variations with pressure and pulse length; the curves are self consistent between the two figures.

The results show that there is a minimum at pressures between 1 and 3 torr in the power required to create the plasma. Theory suggests that the minimum occurs at pressures where the electron collision frequency equals the microwave frequency, $\nu_e \equiv \omega_{\text{pump}} = 1.8 \times 10^{10}/\text{s}$, which implies that $\nu_e = (6-18) \times 10^9/\text{s-torr}$. The lower value is near the maximum electron collision frequency, which occurs at electron energies around 10 to 20 eV [YAM86]. Such electron energies during the avalanche process are consistent with values deduced from optical emission measurements [Ar88, Ec88].

The results also show in a very convincing way that the threshold power decreases systematically with increasing pulse length but the threshold energy *increases* with increasing pulse length or decreasing power. These trends are the same as those reported

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Figure 16. Threshold power required to produce detectable plasma as a function of pulse length and pressure.

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Figure 17. Threshold energy required to produce detectable plasma as a function of pulse length and pressure.

earlier for full breakdown to a critically dense plasma [Ar88], which is not surprising, since we observed that the difference in power required to produce a low density plasma was only marginally less than that required for full breakdown. In fact, in some conditions we were unable to produce less than a full breakdown. The threshold powers in Figure 16 are about one-tenth those previously measured in the same facility [Ar88] at the lowest pressures, but the two sets of measurements agree within a factor of 2 for pressures of 0.1 torr and above.

CONCLUSIONS

Microwave cavity perturbation measurements in the LLNL AIM facility using a 329-MHz cavity have allowed us to examine in detail the plasma formation and decay processes for electron densities between approximately 10^5 and $10^7/\text{cm}^3$. We believe these to be the lowest density plasmas ever studied in microwave breakdown experiments, and as such they allow us to determine the power and energy required to produce plasmas suitable for HF radar reflection as well as the effective lifetimes of these plasmas before re-ionization is required. Analyses of these results leads to the following conclusions.

- For microwave breakdown pulses varying from 0.6 to 2.4 μs , the threshold power required to produce measurable plasmas is 30 to 12 MW/m^2 at 0.01 torr, decreasing to 3.5 to 1.8 MW/m^2 at 1 to 3 torr, and then increasing to 5 to 3.5 MW/m^2 at 30 torr. The threshold power in each case decreases with increasing pulse length, but the required pulse energy *increases* with decreasing power or increasing pulse length. This observation contradicts the predictions of Papadopolous [Pa88] but is consistent with previous measurements of the energy required to produce full microwave breakdown.
- The effective electron density decay rates are approximately $10^2/\text{s}$ for 0.1 to 1 torr, after which they increase linearly with pressure. Thus, the useful plasma lifetimes are in the range of 20 to 40 ms at the lower pressures and decrease to about 1 ms at 30 torr. The decays appear to be due to some combination of diffusion and recombination for pressures below 1 torr and to a balance between attachment and detachment at higher pressures. With the assumption that diffusion is not important except at the very lowest pressures, these decay rates and lifetimes should be comparable to those that would exist for artificially ionized regions in the upper atmosphere.
- The collision frequencies measured at pressures of 1 torr and above correspond to electron temperatures of 800 K or less. In fact, the inferred temperatures for $p > 3$ torr are below room temperature. This result may be due to a contribution to the measured conductivity by negative ions.

These results constitute a complete and satisfactory fulfillment of the objectives of the program.

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REFERENCES

- Al89 R. A. Alvarez, Lawrence Livermore National Laboratory (private communication, 1989).
- Ar88 W. T. Armstrong et al., in AFGL-TM-148, Presentations from the Project Forecast II, PT-47 Plasma Defense Technology Artificial Ionization Workshop, held at Air Force Geophysics Laboratory, February 1988. Also Paper 3P14, Fifteenth IEEE International Conference on Plasma Science, Seattle, WA (June 1988).
- Ec88 D. J. Eckstrom, in AFGL-TM-148, Presentations from the Project Forecast II, PT-47 Plasma Defense Technology Artificial Ionization Workshop, held at Air Force Geophysics Laboratory, February 1988. Also Paper 3P18, Fifteenth IEEE International Conference on Plasma Science, Seattle, WA (June 1988).
- EWD87 D. J. Eckstrom, M. S. Williams, and J. S. Dickinson, *Rev. Sci. Instrum.* **58**, 2244 (1987).
- It73 Y. Itakawa, *Phys. Fluids* **16**, 831 (1973).
- MB69 F. J. Mehr and M. A. Biondi, *Phys. Rev.* **181**, 264 (1969).
- McD64 E. W. McDaniel, *Collision Phenomena in Ionized Gases* (John Wiley, New York, 1964).
- Mo47 C. G. Montgomery, *Technique of Microwave Measurements* (McGraw-Hill, New York, 1947).
- Pa88 D. Papadopoulos, in AFGL-TM-148, Presentations from the Project Forecast II, PT-47 Plasma Defense Technology Artificial Ionization Workshop, held at Air Force Geophysics Laboratory, February 1988.
- SDE87 M. N. Spencer, J. S. Dickinson, and D. J. Eckstrom, *J. Phys. D: Appl. Phys.* **20**, 923 (1987).
- SE89 K. R. Stalder and D. J. Eckstrom, "Measurements of Electron Densities and Collision Frequencies in High Power Microwave Breakdown Plasmas in Low Pressure Air," Final Report, Contract No. 9-XD8-3753Q-1, SRI International (March 1989).
- Si89 Gregory E. Sieger, Lawrence Livermore National Laboratory (private communication, 1989).
- SML60 M. C. Sexton, M. J. Mulcahy, and J. J. Lennon, in *Proceedings of the 4th International Conference on Ionization Phenomena in Gases*, Ed. N. R. Nilsson (North Holland, Amsterdam, 1960).

- Sl46 J. C. Slater, Rev. Mod. Phys. **18**, 441 (1946).
- VIS84 A. L. Vikharev, O. A. Ivanov, and A. N. Stepanov, Sov. J. Plasma Phys. **10**, 460 (1984).
- YAM86 J. H. Yee, R. A. Alvarez, D. J. Mayhall, D. P. Byrne, and J. DeGroot, Phys. Fluids **29**, 1238 (1986).

APPENDIX

MICROWAVE CAVITY REFLECTION INTERFEROMETER FOR SINGLE-PULSE TRANSIENT CONDUCTIVITY MEASUREMENTS

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