Experimental studies of high-power microwave reflection, transmission, and absorption from a plasma-covered plane conducting boundary

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Experimental studies of the reflection, transmission, and absorption of high-power microwave pulses from a plasma-covered plane conducting boundary are presented. Under optimum conditions, backscattered rf power is attenuated by more than 30 dB over values measured in the absence of the plasma. Measurements of the radial and axial plasma density profiles and the neutral gas pressure near the plane conductor indicate that collisional absorption processes are not the primary source of the observed attenuation in the backscattered microwave signal, and that the plasma density exceeds the critical density over much of the volume nearest the conductor. The effects of a tenfold reduction in the microwave power density on the reflection and absorption characteristics of the system are also reported.

I. INTRODUCTION

Interest in the propagation of coherent electromagnetic radiation in plasmas has been sustained for many years as a result of applications of such studies in such diverse areas as the rf heating of fusion plasmas, plasma-filled microwave tubes and devices, and atmospheric and ionospheric propagation. In recent years, however, the possibility of using artificially produced plasmas in the atmosphere to reflect electromagnetic radiation and allow over-the-horizon radar and communication systems at microwave frequencies has been proposed.[1] In addition, studies have been initiated at several laboratories on the extent to which plasmas can be used in place of more conventional microwave absorbers in certain applications.[2-8] In particular, plasmas may be capable of absorbing microwave radiation over a wider frequency range than can conventional absorbers, and are in principle more controllable.

In the studies reported in this paper, high-power microwave radiation was beamed at a plane conducting surface, and reflected and transmitted rf was carefully measured to provide a baseline against which plasma-induced effects could be compared. A hydrogen plasma was created on the surface of the conducting plate by a number of coaxial plasma guns embedded in the plate, and microwave reflection and transmission was then measured over a wide range of plasma conditions. Side-scattered radiation was also measured in some experiments to determine if the incident radiation was absorbed or scattered by the plasma. Finally, the microwave power density was decreased by an order of magnitude to determine if nonlinear effects could be responsible for the observed attenuation in the reflected microwave signal.

In this paper, the experimental measurements are detailed in Sec. II, and a discussion of possible theoretical causes for the observed absorption is presented in Sec. III. Conclusions are drawn in Sec. IV.

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II. EXPERIMENTS

The general experimental configuration used for studies of microwave reflection, transmission, and absorption from plasma-covered plane conductors is shown in Fig. 1. High-power microwave radiation from a large orbit gyrotron (10 GHz, 100 MW, 30 ns FWHM) is beamed at a 30-cm-diam brass plate inserted as the endstop in a 150-cm-long acrylic vacuum chamber. The vacuum chamber is directly connected to the Gyrotron vacuum system and a vacuum of less than 10^{-4} Torr is maintained throughout the entire experimental system. The phase stability of the large orbit gyrotron (which is driven by a 2-MeV, 2-kA, 30-ns pulse line accelerator) is relatively poor, thus ensuring that any observed reductions in reflected microwave signals are almost certainly not due to standing wave effects. A plasma is created on the surface of the plate by 19 embedded coxial plasma guns discharged using a laser flashlamp pulser. The discharge end of each coaxial plasma gun was coated with a titanium-hydride mixture to ensure a hydrogen-rich plasma. Because the plasma is essentially stationary on the time scale of the microwave pulse, some control over the axial and radial plasma density profile can be achieved by varying the firing delay between the plasma guns and the microwave source and/or the charging voltage on the laser flashlamp pulser.

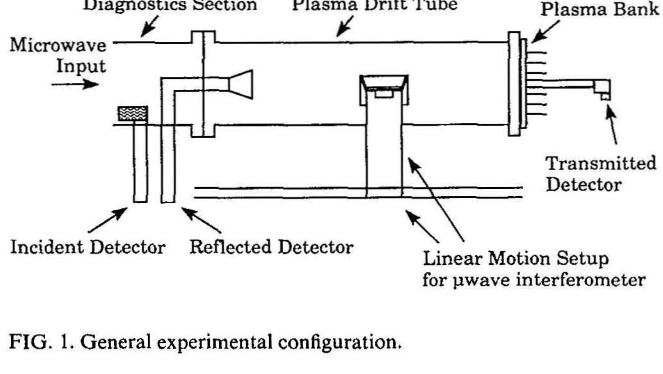


FIG. 1. General experimental configuration.

Measurements of the radial and axial plasma density profiles in the region upstream of the brass plate have been obtained using Langmuir probe measurements and 10 GHz microwave interferometry. Representative Langmuir probe signals 60 cm upstream of the brass plate on-axis are shown in Fig. 2 for 2- and 5-kV flashlamp pulser charging voltages. These results indicate that both the duration and the magnitude of the plasma density waveform at this point can be readily varied by simply controlling the amount of energy supplied to the coaxial plasma guns. Results of detailed studies of the axial plasma density profile (all data taken on axis) as a function of time are shown in Figs. 3 and 4 for 2- and 5-kV flashlamp pulser charging voltages. Plasma density measurements above the critical density for the 10-GHz interferometer (1.2×10^{12} cm^{-3}) were inferred by using both the interferometer data and the Langmuir probe waveforms.

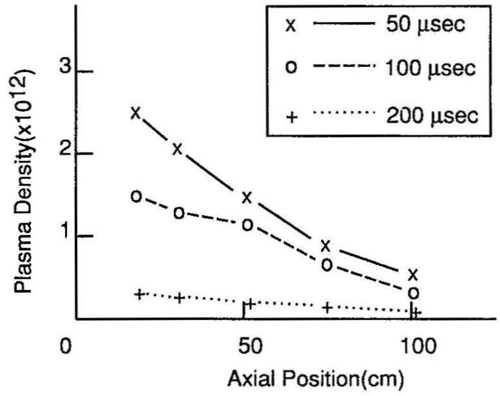


FIG. 3. Axial plasma density distributions at various delay times after plasma gun firing, 2-kV charge on laser flashlamp pulser.

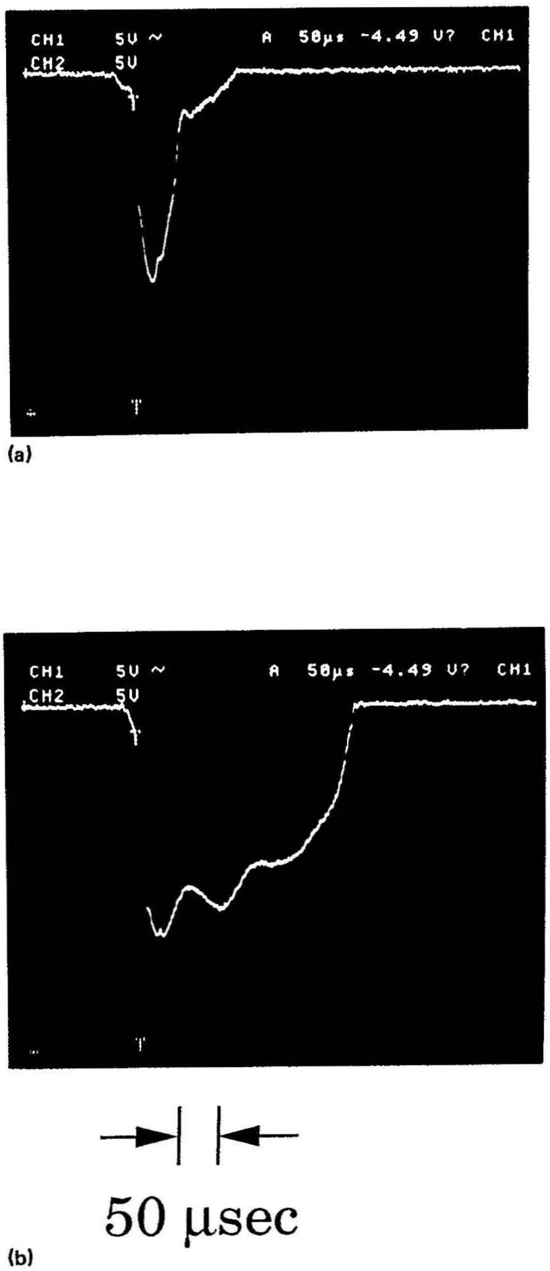


FIG. 2. Typical Langmuir probe waveforms: (a) 2-kV charge on laser flashlamp pulser, (b) 5-kV charge.

Langmuir probe measurements of the radial plasma density profile 60 cm upstream of the brass plate are shown in Figs. 5 and 6 for 2- and 5-kV flashlamp pulser charges, respectively. To determine shot-to-shot variability in the measurements, two measurements were made for each radial position. The nonreproducibility of the data is attributed to the fact that not all of the coaxial plasma guns were observed to fire on every shot, resulting in some shot-to-shot inconsistency in the plasma density profile even well upstream of the brass plate.

The microwave diagnostic setup used in the experiments is shown schematically in Fig. 1. Additional details on the incident and reflected rf monitors are provided in Fig. 7. Not shown in the figure is a standard gain horn employed in the reflected microwave monitor to ensure sufficient directionality. As shown in Fig. 1, a third microwave monitor was inserted right in the brass plate to provide information on the microwave power that was able to propagate through the plasma. A number of tests of the diagnostic system were conducted in advance of the plasma absorption tests, including a test in which the brass endplate was covered with conventional microwave absorber of known attenuation at 10

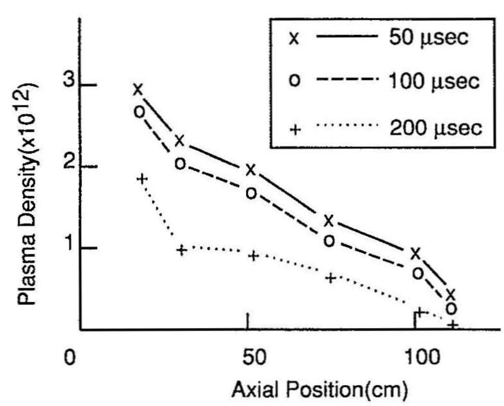


FIG. 4. Axial plasma density distributions at various delay times after plasma gun firing, 5-kV charge on laser flashlamp pulser.

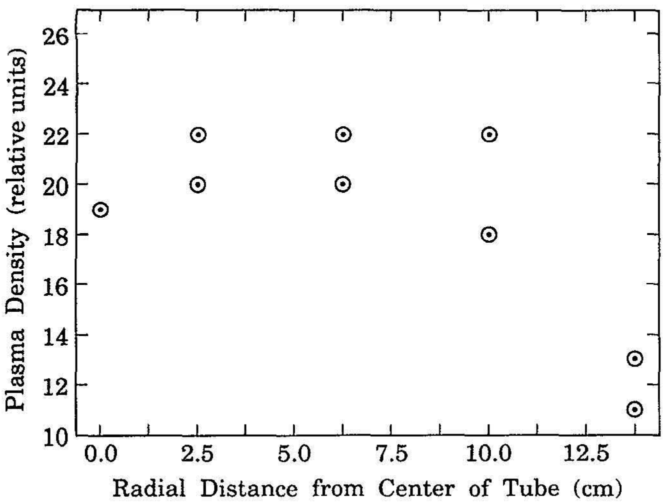


FIG. 5. Radial plasma density distribution 60 cm upstream of plane conductor 70 μs after plasma gun firing, 2-kV charge on laser flashlamp pulser.

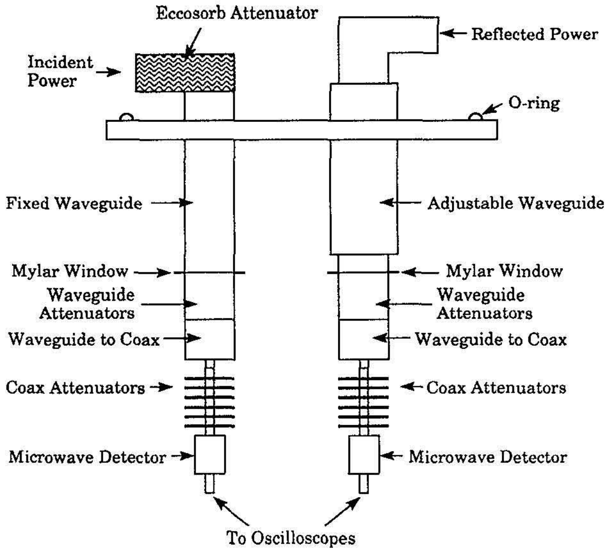


FIG. 7. Incident and reflected microwave detector configurations.

GHz. The attenuation of the reflected microwave signal observed in these experiments compared to that received with no absorber in place was in good agreement with the manufacturer's specifications for the absorber. In a second test, the incident and reflected microwave receiving antennae were each covered with copper foil in turn, and observed microwave signals dropped to levels below ambient noise levels. This test was conducted to ensure that rf leakage around waveguide flanges or coax connections would not corrupt microwave measurements. Finally, the radial profile of the microwave radiation produced by the large orbit gyrotron was measured by rotating the reflected rf antenna so that it received the incident microwaves. This antenna was then moved radially and the microwave power received was normalized to that received by the incident rf monitor, as shown in Fig. 8. Several measurements were obtained for each radial position. As can be seen, the incident microwave radiation is fairly uniform over the cross section of the 30-cm-diam vacuum chamber, with the approximately 6 dB increase in the incident microwaves measured by the "reflected" rf monitor attributable to the 6-dB standard gain horn used on that detection system. Shot-to-shot variations, however, are relatively large.

Typical reflected microwave signals with and without plasma are shown in Fig. 9. It is readily seen that under optimum conditions the presence of the plasma results in a significant reduction in the reflected microwave signal. Figures 10 and 11 present results of extensive measurements of the reflected rf signal (normalized to the incident rf on each shot) as a function of the firing delay between the coaxial plasma guns and the microwave pulse. The system reflection baseline limits represent the range of results obtained with

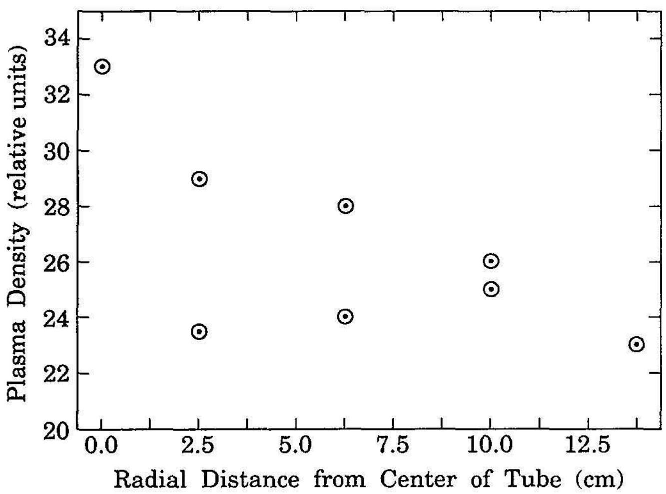


FIG. 6. Radial plasma density distribution 60 cm upstream of plane conductor 70 μs after plasma gun firing, 5-kV charge on laser flashlamp pulser.

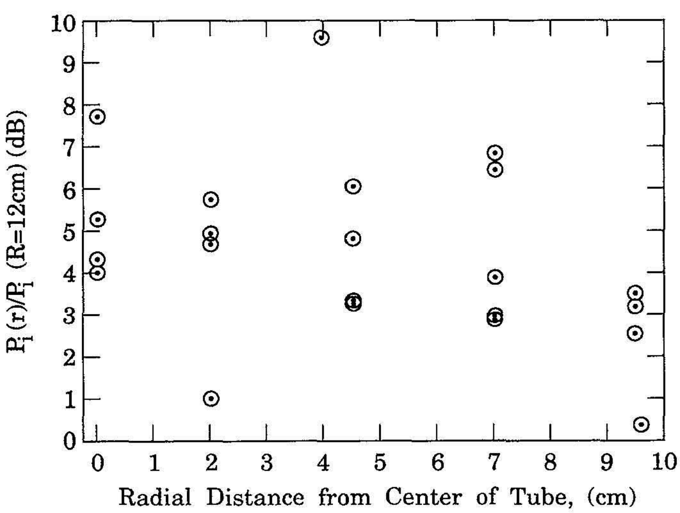
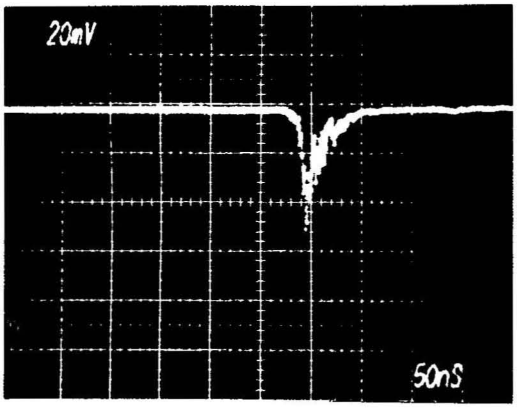
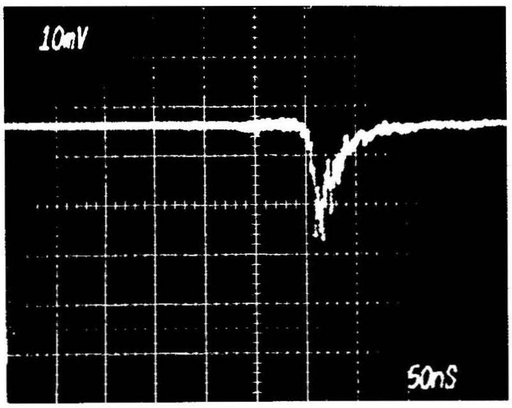


FIG. 8. Normalized incident microwave power density vs radius 150 cm upstream of plane conductor.





(b)

FIG. 9. Typical rectified reflected microwave waveforms: (a) no plasma, 56-dB fixed attenuation, (b) with plasma (5-kV charge, 50 μm delay), 36-dB fixed attenuation.

no plasma over many shots. Data are once again shown for 2- and 5-kV charging voltages on the laser flashlamp pulser. It is evident that the maximum attenuation of the reflected signal due to the presence of the plasma is in the range 20–33 dB under optimum conditions in both cases. The range of firing delays over which significant attenuation is observed is much more narrow for the 2-kV charging voltage, however, consistent with the much shorter plasma lifetime associated with this condition. It is interesting to note that some attenuation is observed for firing delays as large as 200 μs, even though the Langmuir probe measurements indicate that the plasma pulse duration is no more than about 100 μs, 60 cm upstream of the plane conductor. Reflected rf was also found to be fairly uniform over the cross section of the 30-cm vacuum chamber, at least at the axial position of the reflected microwave monitor.

Results of measurements obtained from the transmitted rf monitor located on the brass plate are shown in Fig. 12. The magnitude of the normalized baseline measured without plasma is related to the coupling of rf to the receiving waveguide and should not be used as an indication of the absolute microwave power density reaching the plate. Nevertheless, it is clear from the figure that this signal is strongly attenuated over the same range of firing delays that resulted in significant attenuation of the reflected rf signal, although not at as high a rate as simple evanescent decay of the wave in the overdense region near the plate would imply.

In order to ensure that the plasma was not simply scat-

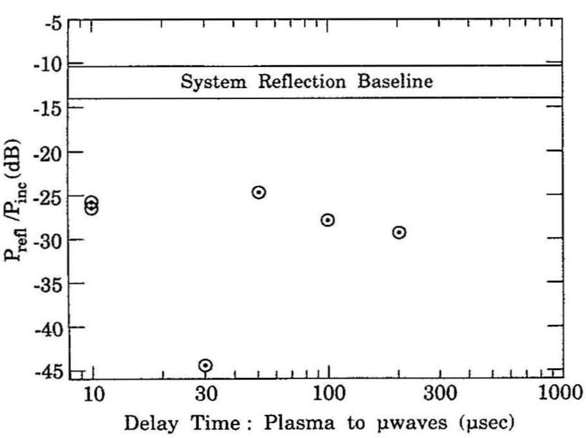


FIG. 10. Normalized reflected microwave power as a function of delay time between firing of plasma guns and the microwave pulse, 2-kV charge.

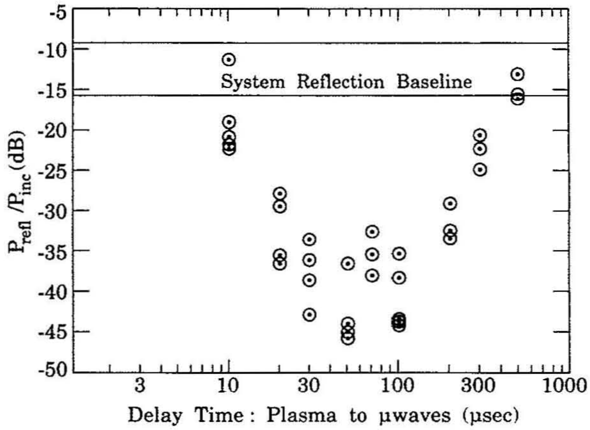


FIG. 11. Normalized reflected microwave power as a function of delay time between firing of plasma guns and the microwave pulse, 5-kV charge.

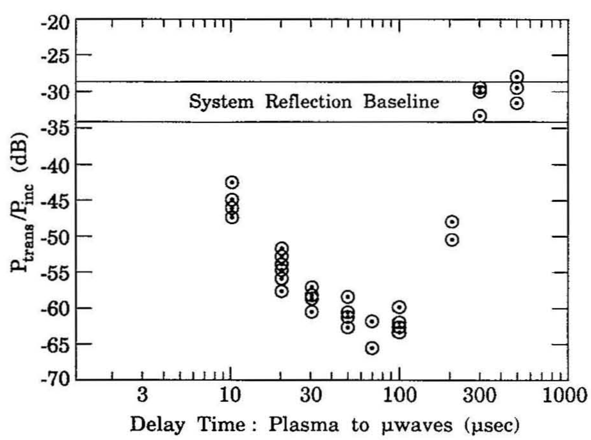


FIG. 12. Normalized transmitted microwave power as a function of delay time between firing of plasma guns and the microwave pulse, 5-kV charge.

tering the rf out the sides of the acrylic vacuum chamber, a third microwave detector was mounted on the side of the vacuum chamber at an axial distance of 75 cm from the brass plate. This detector measured rf exiting radially out of the vacuum chamber and the standard gain horn employed had an acceptance angle of about 30°. Results of these measurements, shown in Fig. 13, indicate that there is not a significant increase in side-scattered rf at firing delays corresponding to significant reductions in the reflected rf signal. In fact, side-scattered rf appears also to be reduced by the presence of the plasma, especially at a firing delay of 50 μs. In this figure, the zero delay time data corresponds to not firing the plasma guns, and therefore approximates the normalized baseline for these measurements.

In a final experiment, the total microwave power from the large orbit gyrotron was reduced by an order of magnitude to about 10 MW to determine if nonlinear effects were an important cause of the observed rf absorption. As shown in Fig. 14, the maximum attenuation of the reflected signal under optimum plasma conditions in this case was about 20–25 dB below the normalized baseline, compared to about 30 dB for the higher power experiments. Thus it is possible that nonlinear effects may play a role in explaining the observed effects.

III. THEORETICAL DISCUSSION

Many mechanisms can produce electromagnetic wave energy absorption in plasmas, including electron-ion and electron-neutral collisional absorption, cyclotron resonance absorption, instabilities, and other nonlinear effects. In this section we will briefly address each of these possibilities with the exception of cyclotron resonance absorption. We are omitting this possibility because there is no applied magnetic field in the wave-plasma interaction region.

The damping constant for an electromagnetic wave propagating in a homogeneous plasma in which the electron-ion collision rate ν_{ei} is given by

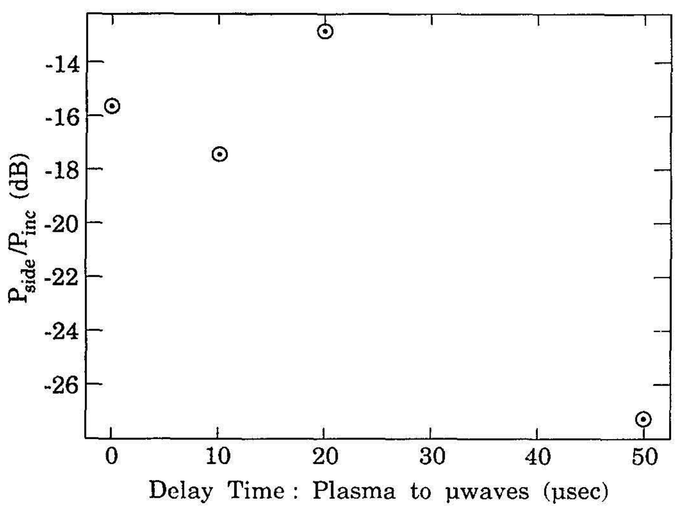


FIG. 13. Normalized side-scattered microwave power as a function of delay time between firing of plasma guns and the microwave pulse, 5-kV charge.

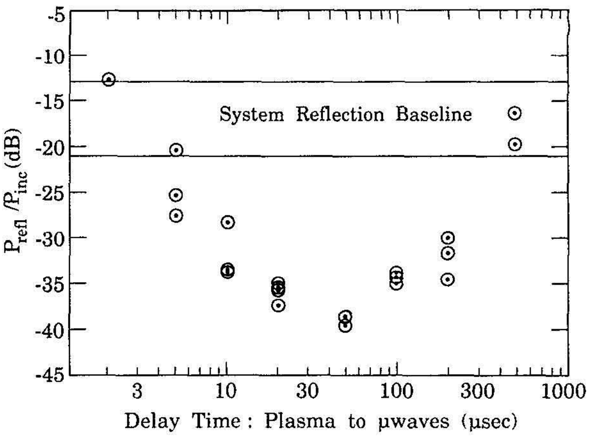


FIG. 14. Normalized reflected microwave power as a function of delay time between firing of plasma guns and the microwave pulse, 5-kV charge, reduced microwave power density.

$$k = \frac{\omega_{pe}^2}{\omega_0^2}\left(\frac{1}{1-\omega_{pe}^2/\omega_0^2}\right)\frac{\nu_{ei}}{c}, \tag{1}$$

where ω_0 is the wave frequency, $\omega_{pe} = (ne^2/\epsilon m)^{1/2}$ is the electron plasma frequency, ϵ is the permittivity of free space, and c is the velocity of light in vacuum.[9] Here m is the electron rest mass, e is the electronic charge, and n is the electron density. For inhomogeneous plasmas the damping factor is somewhat different, although not so different as to change the overall picture. Clearly wave damping will be strongest near $\omega_0 = \omega_{pe}$. To see effective wave damping from electron-ion collisions, therefore, $(\nu_{ei}/c)\,L \geqslant 0.5$ near $\omega_0 = \omega_{pe}$ where L is a characteristic scale length for the plasma. If $L = 10$ cm, the electron-ion collision frequency must therefore be at least 10^9 s^{-1}. At the critical density of $n = 1.2\times10^{12}$ cm^{-3}, and taking $T_e = 2$ eV (a value approximately equal to the electron oscillation energy in the wave electric field), the electron-ion collision frequency is estimated to be 2.5×10^7 s^{-1}. Thus for these experiments the electron-ion collision frequency is simply too small to account for significant wave damping.

A second possible collisional absorption process is wave energy loss to electron-neutral collisions, in which it is assumed that the plasma is immersed in a dense neutral background. Electron-neutral collisional absorption has been observed in high-power microwave propagation experiments[10] in which a high-power microwave pulse is used to break down the atmosphere and subsequent wave energy is coupled to the neutral background by the plasma electrons. For electron-neutral collisions to be a significant source of wave energy damping, however, the ambient neutral gas pressure must be at least 1 Torr assuming $n = n_{crit}$ and $T_e = 2$ eV as discussed previously. Since the actual ambient pressure in the vacuum chamber is initially about 1 mTorr and is not observed to rise significantly when the plasma guns are fired, electron-neutral collisions are also not a likely source of the observed wave attenuation.

A number of instabilities are also candidates for wave energy loss, including the oscillating two-stream instability,[11] the ion acoustic decay instability,[12] the two-plasma decay instability[13] and instabilities driven by stimulated Raman scattering[14] and stimulated Brillouin[15] scattering. Of these, even at the high microwave intensity associated with the experiments, the oscillating two-stream instability appears to be the only one with sufficiently high growth rates to significantly affect the wave amplitude on the 30 ns time scale of the experimental microwave pulse. This instability occurs near $\omega_0 = \omega_{pe}$, and for a homogeneous plasma has a threshold for instability given by

$$\left(\frac{v_{osc}}{v_e}\right)^2 \geqslant 4\frac{\nu_{ei}}{\omega_0}, \tag{2}$$

where v_{osc} is the electron oscillation velocity in the wave field, and v_e is the electron drift velocity. The oscillating two-stream instability is characterized by a very high growth rate with *e*-folding times estimated to be subnanosecond for the experimental parameters reported here.

Another possible mechanism has been investigated by Rowland,[16] who has studied numerically anomalous absorption processes in collisionless plasmas. In this work, the presence of transverse structure in a plasma at the critical density layer is reported to increase the coupling between the electromagnetic wave and electrostatic plasma waves and lead to enhanced absorption of the radiation. Simulations show 90% absorption of the incident wave energy and a reduction in the backscattered rf by 20 dB.

IV. CONCLUSIONS

A significant (20–33 dB) reduction in the backscattered microwave signal from a plane conductor has been observed when a plasma is created on the surface of the conductor under optimum conditions. Measurements of the plasma and ambient neutral densities indicate that the primary absorption mechanism is not collisional in nature. Although it is possible that either the oscillating two-stream instability or the coupling of electromagnetic wave energy to electrostatic waves resulting from a transverse density structure at the critical density layer may account for the observed attenuation in the backscattered rf, further experimental and theoretical work will be required to definitively determine the loss mechanism. For example, predetermined transverse structures can probably be created by creating plasma at only a few of the 19 coaxial plasma guns located on the brass plate. Future studies will concentrate on a careful determination of the loss mechanism and on its possible enhancement.

ACKNOWLEDGMENTS

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[1] R. J. Vidmar, IEEE Trans. Plasma Sci. **18**, 733 (1990).

[2] R. J. Barker, 1990 IEEE International Conference on Plasma Science (Oakland, CA, May 21–23, 1990), Conf. Record, p. 169.

[3] J. E. Brandenburg, W. M. Bollen, R. Seely, and D. Felinczak, 1990 IEEE International Conference on Plasma Science (Oakland, CA, May 21–23, 1990), Conf. Record, p. 170.

[4] D. G. Gregoire, J. Santoru, and R. W. Schumacher, 1990 IEEE International Conference on Plasma Science (Oakland, CA, May 21–23, 1990), Conf. Record, p. 170.

[5] M. Rader, F. Dyer, A. Matas, and I. Alexeff, 1990 IEEE International Conference on Plasma Science (Oakland, CA, May 21–23, 1990), Conf. Record, p. 171.

[6] S. P Kuo and A. Y. Ho, 1990 IEEE International Conference on Plasma Science (Oakland, CA, May 21–23, 1990), Conf. Record, p. 171.

[7] L. H. Combs, C. Liu, and J. R. Roth, 1990 IEEE International Conference on Plasma Science (Oakland, CA, May 21–23, 1990), Conf. Record, p. 151.

[8] J. E. Scharer, O. C. Eldridge, M. H. Bettenhausen, N. T. Lam, and S. W. Lam, 1990 IEEE International Conference on Plasma Science (Oakland, CA, May 21–23, 1990), Conf. Record, p. 151.

[9] W. L. Kruer, *The Physics of Laser Plasma Interactions* (Addison-Wesley, New York, 1988), pp. 46–48.

[10] C. A. Sullivan, W. W. Destler, J. Rodgers, and Z. Segalov, J. Appl. Phys. **63**, 5228 (1988).

[11] W. L. Kruer, *The Physics of Laser Plasma Interactions* (Addison-Wesley, New York, 1988), pp. 61–69.

[12] W. L. Kruer, *The Physics of Plasma Interactions* (Addison-Wesley, New York, 1988), pp. 66–68.

[13] W. L. Kruer, *The Physics of Plasma Interactions* (Addison-Wesley, New York, 1988), pp. 81–83.

[14] W. L. Kruer, *The Physics of Plasma Interaction* (Addison-Wesley, New York, 1988), p. 73.

[15] W. L. Kruer, *The Physics of Plasma Interactions* (Addison-Wesley, New York, 1988).

[16] H. L. Rowland, Phys. Fluids (submitted). [See also 1990 IEEE International Conference Plasma on Science (Oakland, CA, May 21–23, 1990), Conf. Record, p. 150.]