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MICROWAVE CROSS SECTION OF AN IONIZED CHANNEL

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Abstract

At normal incidence, the back scattered, forward scattered and 90° scattered cross sections of the beam were measured at 24 GHz for air and nitrogen at 500 torr pressure. For a single pulse, the measured radius of the beam was 4.3 mm at $Z = 80$ cm, whereas in a burst the radius decreased to 2.5 mm for the fifth pulse. This corresponds to a density reduction of a factor of 5 and corresponds to a channel temperature of 1200° C. Within experimental error, the observed cross sections were those to be expected from a metal rod of these dimensions. There was no evidence of any enhancement in cross section at long times as might be expected from a hydrodynamic channel instability. However, receiver noise would have masked any fluctuations present.

The cross sections were also measured with the microwave beam forming an angle of 10° with the electron beam. The backscatter cross section and the bistatic cross section to a second antenna forming an angle of 10° with the beam was also measured. In air, the bistatic and monostatic cross sections were approximately 10 db higher than expected from the beam size measurement, i.e., the returns observed were those one would expect from a good conducting rod approximately 5 cm radius. In nitrogen, the bistatic cross section was the same as air, but the monostatic cross section was 30 db larger than expected. This result is probably due to sausageing induced in the channel by an axial magnetic field. It could, however, be an indication of a fast growing hydrodynamic instability.

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For both measurements, the cross section in air decayed due to oxygen attachment with a time constraint of approximately one microsecond. In nitrogen, the primary electron loss process is recombination which gave a characteristic loss time on the order of 10 microseconds.

Introduction

The effective microwave cross radius section of a channel made by an energetic electron beam depends on several physical phenomena. First, the effective microwave radius can be considerably larger than the channel radius because of the way microwaves interact with the channel. Second, the channel can be considerably larger than the beam, particularly if the beam is sufficiently powerful to induce a strong radial shock wave that ionizes the gas for a distance out from the axis. Third, the microwave cross section can be strongly enhanced at small angles if axial modulations of channel density that result from a hydromagnetic instability are present. In this report the results of an experiment are presented wherein an attempt was made to measure at 1.2 cm the microwave cross sections of channels produced in air and nitrogen by a 400 ampere, 300 nsec electron beam.

An Estimate of Microwave Radius

In this section we examine the first phenomena mentioned above since it is perhaps the most relevant for the experiments reported here. We assume that the gas does not respond to the beam and that the channel is simply described by the parameters of the electron beam.

Consider a beam of current I traveling through a gas at pressure p . Lee (1) has shown that we should expect the beam current density to have a Bennett profile as a function of radius that is

$$J_{\beta}(t) = \frac{I}{\pi a^2 \left[1 + \left(\frac{r}{a} \right)^2 \right]^2} \quad (1)$$

where a is the Bennett radius. Thus a is the measure of the beam radius; it is the order of a few millimeters in these experiments. The beam, in going through the gas, causes ionization by direct deposition, and the conservation equation for free electrons in the gas is

$$\frac{dn}{dt} = \frac{J_{\beta} dE/dx}{eW} - \nu_a n. \quad (2)$$

Here we have assumed that the electrons are created only by direct deposition and lost only by attachment at a rate ν_a . Recombination can be added by adding the term $-\alpha n^2$ to the equation where α is the recombination coefficient. Solving equation (2) we find

$$n = \frac{n_0}{[1 + (r/a)^2]^2} \quad (3)$$

during the pulse and

$$n = \frac{n_0}{[1 + (r/a)^2]^2} e^{-\nu_a t} \quad (4)$$

after the pulse where

$$n_0 = \frac{I}{\pi a^2} \frac{dE/dx}{\nu_a eW} \quad (5)$$

In air, the largest attachment cross section is (2) three body attachment which is given by

$$\nu_a = 10 p^2 \left(\frac{300}{T} \right)^3 e^{-600/T} \quad (6)$$

Here we have assumed that the electrons and gas are at the same temperature T and that p is the pressure in atmospheres. Let us assume $T = 1000$ °K in which case

$$v_a = 1.5 \times 10^8 p^2 \quad (7)$$

Evaluating (5) for air then gives

$$n_0 \approx 10^{12} \frac{I}{p a^2} \quad (8)$$

For most beam current densities of interest, the electron density in the channel created by the beam will be much greater than the critical density at the microwave frequency. Therefore, as a crude model, assume that the channel as seen by the microwaves is that of a good conductor with radius such that $n = n_{\text{critical}}$. One finds the microwave radius r_μ given approximately by

$$r_\mu = \left(\frac{I a^2}{\pi} \frac{dE/dx}{v_a e W n_{\text{crit}}} \right)^{1/4} e^{-\frac{v_a}{4} t} \quad (9)$$

$$\text{using } n_{\text{crit}} = 10^{-6} m_e \omega^2 / e^2 = \left(\frac{f}{9000} \right)^2 \times 10^{18}$$

one finds

$$r_\mu = 3.0 \left(\frac{I a^2}{p f^2} \right)^{1/4} e^{-37.5 p^2 t} \quad (10)$$

Here r_μ is in cm if I is in amperes, a is in cm, p is in atmospheres, f is in GHz, and t is in microseconds.

A similar calculation for a recombination dominated loss process yields

$$r_\mu = \left(\frac{I a^2}{\pi e W \alpha n_{\text{crit}}^2} \frac{dE/dx}{n_{\text{crit}}} \right)^{1/4} (1 - \alpha t n_{\text{crit}})^{1/2} \quad (11)$$

For nitrogen we will assume that $\alpha = 10^{-7}$ in which case we find

$$r_{\mu} = \frac{56.8}{f} (I a^2 p)^{1/4} [1 - (\frac{f}{28.5})^2 t]^{1/2} \quad (12)$$

where the parameters have the same units as in equation (10). These calculations are only valid if the microwave radius r_{μ} is greater than the Bennet radius a .

According to Ref. (3), pages 210, 273, and 304, the bistatic cross section of a perfectly conducting cylinder of radius a and length $2h$ is given by

$$\sigma(\psi_i, \psi_s) = \frac{4\lambda a}{2\pi} \frac{\cos^2 \psi_s}{\cos \psi_i} \left\{ \frac{\sin[\frac{2\pi h}{\lambda} (\sin \psi_i + \sin \psi_s)]}{\sin \psi_i + \sin \psi_s} \right\}^2 \quad (13)$$

This result is valid for either polarization if

$$\frac{2\pi a \cos \psi_i}{\lambda} > 1 \quad (14)$$

For the narrow angle experiment reported here, the angles are defined in Ref. (3) such that $\psi_s = 180^\circ - 80^\circ$ and $\psi_i = 80^\circ$. For the signal coupled from one antenna to the other and $\psi_s = \psi_i = 80^\circ$ for the monostatic cross section, we then find that both cross sections for this experiment are given by

$$\sigma = \frac{\lambda a}{2\pi} \cos(80^\circ) \sin\left[\left(\frac{4\pi h}{\lambda}\right)\right]^2 \quad (15)$$

where we have approximated $\sin 80^\circ = 1$. Thus the cross section is independent of the length except for the term in brackets that varies from zero to one and back every time the length increases by one quarter wavelength.

Experimental Apparatus

The microwave cross section experiment was conducted in the compression apparatus shown in Fig. 1. The experiments were done in both dry air and nitrogen at pressures up to 500 torr. For all experiments, an axial magnetic field of 7.5 kGauss was applied to increase the beam current density and thereby greatly increase the gas heating.

The electron beam was generated by the Astron accelerator, and had a voltage of 5 MeV at a current of 400 amps and a pulse width of 300 nsec for these experiments. The accelerator was pulsed, either twice per second or in a burst of five pulses every 2-1/2 seconds. In the burst, the pulses were separated by 1.2 msec.

The microwave setup used for the experiment is shown schematically in Fig. 2. A K band klystron which generates 3 watts at 24 GHz was located outside the shielding in a microwave screen room approximately 60 ft. from the experiment. The energy was coupled to the transmitting antenna through K band wave guide, with a power loss of less than 10 db. The antenna was matched to the line by tuning the reflected power to a minimum with the E-H tuner at the transmitting antenna. By careful adjustment, the antenna could be matched such that the reflected power (P_-) was more than 70 db below the forward power (P_+). It was, however, difficult to retain this balance due to thermal drifts of various microwave components and small frequency drifts of the klystron. In practice, it was found that a good balance could often be recovered by varying the repeller voltage of the klystron and observing the null.

The power transmitted through the system (P_T) was maximized in the absence of a beam by adjusting the E-H tuner on the receive antenna. It was found that the attenuation of signal between the transmit and receive antennae was 16 db for the normal incidence experiment.

The 90° scatter antenna was tuned by setting the microwave attenuator in the reference line (the line that couples some P_+ into P_S) to a maximum and adjusting the E-H tuner at the scatter horn to maximize the scattered power P_S . This signal was typically 45 db below P_+ . The scattered power was then nulled to more than 80 db below the forward power by adjusting the attenuator and phase shifter in that reference line. The three signals were coupled back to the microwave screen room through three wave guide runs to a microwave switch which was connected to the microwave receiver.

The microwave receiver consisted of a Hewlet Packard K band oscillator set at 24 GHz - 100 MHz, a crystal mixer, and a Tektronix 7L12 spectrum analyzer adjusted to the difference frequency ≈ 100 MHz. The rise time of the receiver was then determined by the bandwidth of the spectrum analyzer. During all the experiments this bandwidth was kept at 3 MHz, giving a rise time of 0.1 μ sec.

Microwave measurements at the experiment were made by measuring the four powers, P_+ , P_- , P_T and P_S , at the experiment with microwave power meters and simultaneously with the microwave receiver in the screen room. In this way, measurements in the screen room were converted to equivalent measurements at the experiment. In practice, the forward power P_+ was found for each experiment by adding 16 db to the measurement of P_T in the absence of a beam. In this way, variations in the receiver sensitivity were eliminated from the measurements.

In the experiments reported here, three antenna configurations were used:

- A) Normal incident, E field perpendicular to the beam. This configuration is shown in Fig. 3.
- B) Normal incidence, E field parallel to the beam. The three antennae shown in Fig. 3 were rotated 90°.

- C) Narrow angle measurement. Two of the microwave horns were mounted to the face plate of the tank and aimed at an angle of 10° with respect to the beam. A picture of the antennae mounted in the plate is shown in Fig. 4. The electric field of the wave was polarized so that it lay in the plane containing the axes of the antennae and the beam.

For all experiments, the Astron beam terminated at the X-Y-Z Faraday probe. This device was also used to measure the beam size for each condition. The region of the X-Y-Z Faraday probe struck by the beam can be seen in Fig. 3. For the experimental configurations A and B wherein the direction of microwave propagation was perpendicular to the beam, the Faraday probe was positioned 40 cm beyond the microwave antennae. For the narrow angle experiment, the Faraday probe was positioned approximately 2 meters from the antennae. The interior of the experimental vessel was lined with the microwave absorber AN72 manufactured by Emerson and Cummings, Inc. At K band, the power level of a normally reflected wave from this material can be expected to be 20 to 25 db below the incident wave. The spurious coupling between antennae was nulled by using a reference signal derived from the input line.

Following a suggestion by Paul Sheldon (4) of the Naval Research Laboratory, the microwave antennae were designed using a rear feed system for polarized reflectors developed by A. C. Studd (5). The dishes are not paraboloids, but rather are sections of a sphere. Moreover, the caps on the waveguides visible in Fig. 3 which direct the energy back at the dishes distort the pattern when the focal point of these dishes is adjusted to 15 cm (the beam axis). Some of the bench tests of these antennae are presented in Appendix 1.

Experimental Results

A summary of the experimental results obtained at 500 torr pressure is presented in Fig. 5. Here the peak cross section obtained at the time of the pulse is presented for the three experimental configurations. Also presented for comparison is the signal obtained when a long 1/2-inch diameter metal rod was inserted between the horns (see Appendix 1). Thus both the monostatic and 90° bistatic cross sections are smaller than those of a 1/2-inch metal rod at normal incidence. However, the cross sections at 10° incidence are larger than those of the rod, and in particular the monostatic cross section in nitrogen is more than 30 db larger than that of the rod.

A collection of oscillograms showing the effects of bursting 5 pulses into both 500 torr air and nitrogen is shown in Fig. 6. Also shown is the beam current and beam profile for each of the 5 pulses as measured with the X-Y-Z Faraday probe. The first pulse of the burst generated the lowest string of dots in Fig. 6, which shows the beam current density profile as measured at ambient temperature and 500 torr. The upper dots show the current density of the 5th pulse. These data indicate that the 5th pulse propagated through approximately 20% of the average density of the first pulse, i.e., the gas temperature just before the 5th pulse is near 1200 °C. The FWHM of the 1st pulse at 500 torr is .85 cm, while the FWHM for the 5th pulse is 0.5 cm.

The transmitted microwave signals show that the channel attenuates the microwaves from 25-30 db in both air and nitrogen. Compare the attenuation resulting from a 1/2-inch metal rod (≈ 5 db) with that produced by the channel (≈ 25 db). The peak cross sections in Nitrogen occur 2-3 microseconds after the pulse, whereas the air cross sections peak during the beam pulse. Notice further that both the back scatter and 90° scatter cross sections in air decay

with time constants less than one microsecond, whereas the decay in pure nitrogen is initially with a time constant near 10 μ sec and at long times near 1000 μ sec. The rapid decays apparent in air are a result of oxygen attachment, whereas the decays in nitrogen are due to recombination.

Figure 7 shows variations of the monostatic and bistatic cross sections for 10° incident and reflected as a function of pressure for both air and nitrogen. Here it can be seen that the two cross sections approach -43 db at low pressures and the bistatic cross section in air approaches -55 db. This variation most likely reflects a change in the collision frequency of the electrons in the channel. At zero pressure, all cross sections are less than the sensitivity of the system.

Figure 8 shows oscillograms of the monostatic and bistatic signals in both air and nitrogen at 500 T pressure. These data were obtained after the large differences between nitrogen and air in the levels of the monostatic signals was discovered. In obtaining these data the gas was changed from nitrogen to air as quickly as possible with the beam conditions and microwave tune unchanged. Notice that nitrogen shows the same delay in peak microwave return of 2-3 μ sec observed in the normal incidence experiment whereas the air returns decay immediately.

Comments and Conclusions

There are several aspects of this experiment that make the results inconclusive. Because of the limited geometry, wall reflections cannot be entirely eliminated. However, the largest source of experimental uncertainty is the axial magnetic field which was used to hold the beam together at the

high pressures of the experiment. First of all, the system was operated close to cyclotron resonance. At 7.5 kGauss, the ratio of cyclotron to microwave frequency was 0.88. However, the ratio of collision to microwave frequency was greater than one, and consequently, the resonance was strongly damped during beam time.

The axial magnetic field also caused the beam to sausage. In the absence of collisions, the magnetic field refocuses the beam every cyclotron wavelength in the field. For this experiment, this length was approximately 15 cm. Figure 9 shows a measurement of the beam sausaging obtained from a previous experiment at 6.8 kGauss. Also shown in this Figure is the beam size versus Z in the absence of an axial magnetic field. Obviously, the magnetic field cannot be eliminated if we want to create a heated channel over an appreciable axial distance. These data were obtained by observing the beam current density along the beam axis with the X-Y-Z Faraday probe. Because of the presence of microwave absorber inside the tank, the X-Y-Z Faraday probe could not be moved in the Z direction in the present experiments.

The entrance aperture may also have been limiting the beam cross section as seen by the microwaves. As previously discussed, the microwave cross section should be very sensitive to the wings of the beam, since the radius at critical density is considerably larger than the beam radius.

Nevertheless, one can calculate a microwave cross section based on the experimental data contained in Fig. 5. The cross section of the 1/2-inch diameter rod is $2 \times 10^{-2} \text{ cm}^2$ obtained from the radar equation using an antenna gain of 25 db and the experimental data. This is in reasonable agreement with the expected cross section obtained from Eq. (15). The measured cross section of the beam in air is 0.16 cm^2 . This is approximately 25% of the beam area, and implies a beam radius of 5 cm from Eq. (15). The back scatter cross section

in nitrogen is about 25 cm^2 . This is anomalously high, and suggests that a stronger axial dependence to the channel is present in nitrogen than in air.

On the basis of these data, the channel made by the beam appears to the microwaves as being equivalent to a perfectly conducting rod of approximately the same radius as the electron beam. At narrow angle incidence in the presence of an axial field, the microwave cross section in air is enhanced by approximately a factor of ten, possibly due to beam sausageing induced by the magnetic field.

In nitrogen it was discovered that all the cross sections peak two to three microseconds after the Astron beam pulse. This is most likely due to a radial shock wave generated by the gas by the electron beam. As the shock wave moves radially outward, the radius at which $n = n_{\text{critical}}$ moves outward resulting in a larger channel and consequently a larger cross section. In air, because of oxygen attachment, the plasma electron density drops too rapidly to observe this phenomenon.

Fluctuations in the microwave returns in nitrogen in both the normal incidence and 10° incidence experiments may be indicative of a hydrodynamic instability that requires 2-3 microseconds to grow to a perceptable amplitude. These fluctuations are not due to microwave receiver noise, since this noise level is approximately 25 db below the observed fluctuation level.

In all experiments, the microwave returns were carefully observed for any evidence of hydromagnetic instability significantly enhancing the microwave cross section at long times. No such instability was observed. The fluctuations observed in nitrogen just after the beam pulse were rapidly obscured by receiver noise as the cross section dropped.

APPENDIX I

Bench Testing the Microwave Antennae

The microwave antennae were designed with the normal incidence experiment in mind. The gap between the end cap and the guide was adjusted to match the antennae to the waveguide with a standing wave ratio less than 1.2. An E-H tuner was then used to accurately match the antennae to the guide. The focal points of the antennae were found by using a small microwave dipole antenna which was moved along the antenna axis. The distance of the end cap from the antenna was then adjusted to control the focal position. The limited geometry of the experimental vessel required the focal point of the antennae to be close to the end cap. As a result, the end cap caused a distortion of the radiation pattern. Figure A1 shows the results of inserting a 3/16 inch diameter rod and a 1/2-inch diameter rod along the axis of the experimental vessel in the position occupied by the beam.

For the narrow angle experiment, the antennae were focused by placing the dipole antennae 50 cm away from the antennae, and the distance from the antennae to the end cap adjusted to maximize the signal. Figure A2 shows the result of inserting both a 1/2-inch metal rod and a metal sphere on the end of the 1/2-inch rod along the beam axis with the two antennae in the experimental vessel in the configuration shown in Fig. 4. As the rod moved along the axis, the signals showed large fluctuations in amplitude, and only the peak signals are shown in Fig. A2. The Radar Cross Section Handbook (Eq. 4.3-43) gives the monostatic and bistatic cross sections for a long 1/2-inch diameter rod of about $3.3 \times 10^{-2} \text{ cm}^2$ which goes to zero every time the rod length times $\sin 80^\circ$ is an integral number of wavelengths. Using this, one can estimate from the radar equation an antenna gain of about 24 db. The sphere can also be used to obtain an estimate of the antenna gain. Using the monostatic

return at 40 cm and the radar equation yields an antenna gain of 22.5 db. At 200 cm, the gain is 24.6 db.

The radiation patterns of the antennae were also measured in a bench set up by rotating one antenna in front of another and measuring the energy coupled between the antennae. In this way it was determined that the beam width at 1/2 power was approximately 15° wide in both the E and H planes. This implies a gain of 23.7 db. The side lobes were from 15 to 20 db below the main lobe in the E-plane and from 12-15 db below the main lobe in the H plane.

Even though the interior of the experimental vessel was lined with microwave absorber, an obvious criticism of the experiment is that the observed microwave signals might result from undesired reflections rather than from the true microwave returns. The fact that the system was able to measure a microwave cross section of the 1/2 inch metal rod at 10° incidence that agrees well with the theoretical prediction suggests that the spurious microwave reflections are not introducing a serious error.

Figure 1

Schematic Diagram of Experimental Vessel

Figure 2

Microwave Plumbing for the 90° Incidence Experiment

Figure 3
Picture of Microwave Antenna 90° Incidence

Figure 4
Picture of Microwave Antennae for 10° Incidence Experiment

Summary of experimental results at 500 Torr

Figure 5

Air

N₂

Figure 6
Oscillograms of Microwave Signals at 500 Torr in Air and Nitrogen
Normal Incidence Experiment

Figure 7
Microwave Cross Sections as a Function of Pressure
10° Incidence Experiment

Oscillograms of Microwave Signals at 500 Torr in Air and Nitrogen
10° Incident Experiment

Figure 8

Figure 9

Beam Radius versus Z at 500 Torr N_2

Figure A1

Normal Incidence E Parallel to Beam

Figure A2

10° Incidence E Parallel to Beam

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