Microwave Propagation through a Plasma in a Magnetic Field

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Experiments have been performed on the propagation of X-band ($\approx 10^{10}$ cps) microwave signals through a plasma in a magnetic field (≈ 4 kG). The direction of propagation was parallel to the magnetic field lines. The regions of transmission and attenuation for both right-hand and left-hand circularly polarized microwave signals were located, at frequencies above and below both the electron cyclotron frequency and the electron plasma frequency. The range of densities covered was approximately 10^{10} electrons/cc to 10^{13} electrons/cc. Over part of this range the density measurements were made using an interferometer operating in both the right-hand and left-hand circularly polarized modes. Values of the refractive index greater than and less than unity were measured. Measurements were also made to determine the effect of electron temperature on the electron cyclotron cutoff frequency for the right-hand circularly polarized mode. A downward shift in the cutoff frequency was observed, which is in agreement with the theory.

INTRODUCTION

MOST experiments on the propagation of microwave signals through a plasma in a magnetic field have, with a few exceptions,[1–3] been designed with the direction of propagation perpendicular to the magnetic field. The investigation reported here is concerned with the attenuation and transmission characteristics when the direction of propagation is parallel or antiparallel to the direction of the magnetic field. There are two possible advantages to using this propagation direction. Firstly, relatively low microwave frequencies may be used, since, using the "whistler" mode, transmission may occur at frequencies below the plasma frequency. Secondly, very high values of the refractive index may be obtained.[3] This means that the microwave phase velocity may become comparable with the electron thermal velocities and leads to the possibility of measuring electron temperatures.[4]

This paper has been divided into two parts, a low-temperature section and a high-temperature section. The low-temperature section deals primarily with interferometric measurements of refractive index and hence electron density, using various propagation modes parallel and antiparallel to the magnetic field. The high-temperature section describes measurements made to test a theory by Drummond,[4] which indicates a possible method of measuring electron temperatures. The plasmas described in the high-temperature section are not necessarily hotter than those described in the low-temperature section. The distinction between high and low applies to the type of measurement made and the method of analysis.

The electromagnetic waves which propagate through a plasma along the magnetic field lines are circularly polarized and the sense of the polarization, right or left hand, is defined with respect to the direction of the magnetic field and not the direction of propagation. For the right-hand circularly polarized mode (often abbreviated as the r mode), the electric and magnetic vectors rotate in the same direction as the electrons gyrate about the magnetic field lines. This is known as the "extraordinary" mode in magneto-ionic terminology. The left-hand circularly polarized (l) mode, referred to the direction of the magnetic field, is known as the "ordinary" mode.

The term "whistler" mode is reserved for the r mode when the microwave frequency is less than both the electron cyclotron frequency and the electron plasma frequency.

LOW-TEMPERATURE SECTION

In the absence of a magnetic field the refractive index N of a plasma is given by

$$N^2 = 1 - \omega_p^2/\omega^2, \tag{1}$$

where ω is the angular microwave frequency and ω_p, the plasma electron frequency, is given by

$$\omega_p^2 = ne^2/m\epsilon_0, \tag{2}$$

where n is the electron concentration, e is the electron charge, m is the electron mass, and ϵ_0 is the permittivity of free space.

In writing Eq. (1) it has been assumed that the positive ions are infinitely massive, that the collision frequency is zero, and that the electrons have no thermal motion. These assumptions are justified in many laboratory plasmas for experiments of the type described in this section. The effects of the introduction of a nonzero electron temperature are discussed in the high-temperature section.

Transmission may occur only when N is real and hence only when ω is greater than ω_p. In the presence of a magnetic field the situation may be significantly altered, particularly if the direction of propagation is

[1] R. M. Gallet, J. M. Richardson, B. Wieder, G. D. Ward, and G. M. Harding, Phys. Rev. Letters **4**, 347 (1960).
[2] T. Consoli, M. Dagai, and D. Lepechinski (unpublished); T. Consoli, R. Geller, and R. LeGardeur, *Proceedings of the Fifth International Conference on Ionization Phenomena in Gases, Munich, 1961* (North-Holland Publishing Company, Amsterdam, 1962); and T. Consoli and M. Dagai, J. Nucl. Energy, Part C **3**, 115–128 (1961).
[3] O. N. Dellis and J. M. Weaver, Nature **193**, 1274 (1962).
[4] J. E. Drummond, Phys. Rev. **110**, 293 (1958); **112**, 1460 (1958).

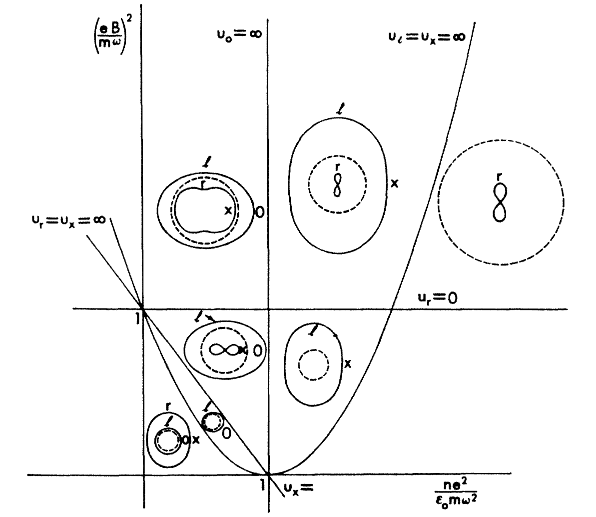


FIG. 1. β^2-α^2 plot and phase velocity surfaces for a plasma in a magnetic field [after Papa and Allis (reference 5) and by courtesy of *Planetary and Space Science.*]

parallel or antiparallel to the direction of the magnetic field. In this case very high microwave frequencies are not required, even for dense plasmas, since transmission may occur at frequencies less than the plasma frequency using the "whistler" mode.

Papa and Allis[5] have given a detailed report of the waves in a plasma in a magnetic field. Figure 1 is a copy of Fig. 1 of their paper, reproduced by permission of the authors and *Planetary and Space Science.* The figure shows how the refractive index squared, N^2, changes sign in the β^2-α^2 plane ($\alpha=\omega_p/\omega$ and $\beta=\omega_c/\omega$, where ω_c is the angular electron cyclotron frequency). N^2 changes sign only when going through zero or infinity. $N^2=\infty$ defines a resonance and $N^2=0$ defines a cutoff.

The β^2-α^2 plane is divided into eight regions using the following two resonance lines and two cutoff lines:

1. Electron cyclotron resonance represented by the horizontal straight line at $\beta^2=(\omega_c/\omega)^2=1$.
2. Plasma resonance represented by the diagonal straight line.
3. Plasma cutoff represented by the vertical straight line at $\alpha^2=(\omega_p/\omega)^2=1$.
4. Cyclotron cutoff represented by the parabola.

Within each region the wave normal surfaces remain topologically the same. Sample wave normal surfaces are drawn in each region. A wave normal surface is a polar plot of the microwave phase velocity, with the vertical direction representing propagation along the magnetic field. The radius of the dashed circle represents the velocity of light in each region.

The prime interest in this document is in propagation along the magnetic field lines and, therefore, usually just the *r* and *l* modes of the Papa and Allis paper, which are the *r* and *l* modes defined in the introduction, are considered. The refractive indices of these modes are given by

$$N_{l,r}^2=1-\alpha^2/(1\pm\beta). \tag{3}$$

The negative and positive signs, in the denominator, refer to the *r* mode and the *l* mode, respectively.

An examination of Fig. 1, or Eq. (3), shows that if $\beta^2>1$, the *r* mode may transmit for all values of α^2. It should be noted that, for this case, the refractive index is greater than unity. When $\alpha^2>1$, this mode is confined to propagation within a cone whose axis is the magnetic field. This is shown by the figure eight shape in the top right-hand corner of Fig. 1. As the value of β^2 approaches unity, i.e., as cyclotron resonance is approached, the semiangle of the cone decreases, until, on crossing the $\beta^2=1$ line, this mode, which is the "whistler" mode, can no longer transmit.

For the *r* mode with $\beta^2>1$ and $\alpha^2<1$, shown in the top left-hand corner of Fig. 1, the wave is no longer confined to a transmission cone, but still has a refractive index greater than unity.

When $\beta^2<1$, the *r* mode may propagate only at low values of α^2, as shown in the bottom left-hand corner of Fig. 1. It then has a refractive index less than unity.

The *l* mode is nowhere confined to a transmission cone and may transmit in the regions indicated in the diagram, where it always has a refractive index less than unity.

The experiments described in this section were made to measure the cutoffs and resonances indicated in Fig. 1, for both the *r* and *l* modes. The refractive index and hence the electron concentration was also measured using each mode.

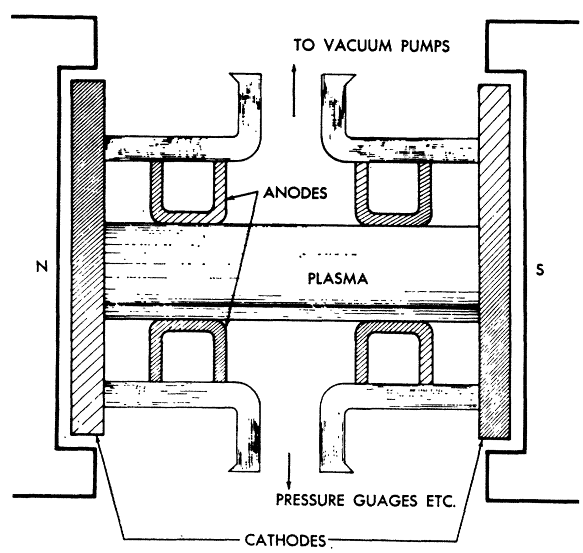


FIG. 2. Discharge vessel configuration.

[5] R. J. Papa and W. P. Allis, Planetary and Space Sci. **6**, 100 (1961).

Apparatus

The plasma was generated by driving current through argon gas, at a pressure of a few microns, in a discharge tube containing electrodes in a Philips Ionization Gauge configuration (see Fig. 2). The cathodes were made of either aluminum or copper. The beam shaping masks, not shown in Fig. 2, were made of an insulating material. The circular aperture of the beam shaping masks was 3.3 cm in diameter and the inner diameter of the anode rings was 7.11 cm. The cathode separation was 14.35 cm.

The vacuum seals were made by compression of neoprene O-rings and all fittings to the tube were of nonmagnetic materials.

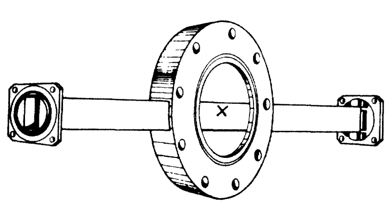
The discharge was pulsed with a pulse duration of a few milliseconds and a pulse repetition rate of 6 per min. The peak current could be varied between 0.01 and 10.0 A.

The complete tube was placed between the pole pieces of an electromagnet which supplied a magnetic field uniform to within one quarter of one percent throughout the operating volume. The magnetic field strength was chosen so that the consequent electron cyclotron frequency was in the middle of the X-band microwave frequency range, approximately 10^{10} cps.

The circularly polarized microwave signals were introduced through the cathodes as shown in Fig. 3. Sections of X-band waveguide were incorporated in each cathode, with the outside surface of one of the broad faces forming part of the cathode surface. A pair of crossed slots was cut in the broad face of each guide. These could be used both to radiate and receive circularly polarized microwave signals,[6] the set of crossed slots in one cathode acting as a radiating and the set in the other cathode as a receiving antenna. Small mica windows were placed in front of each slot to prevent penetration of the plasma into the waveguide.

The radiating slots were used so that they emitted right-hand circularly polarized signals, the sense of the polarization here being referred to the direction of the outward normal from that cathode surface, i.e., to the direction of propagation. These signals could be used as either the r or l mode by changing the direction of the magnetic field.

FIG. 3. Cathode structure showing crossed slot antenna.



[6] A. J. Simmons, IRE Trans. Antennas Propagation AP-5, 31 (1957).

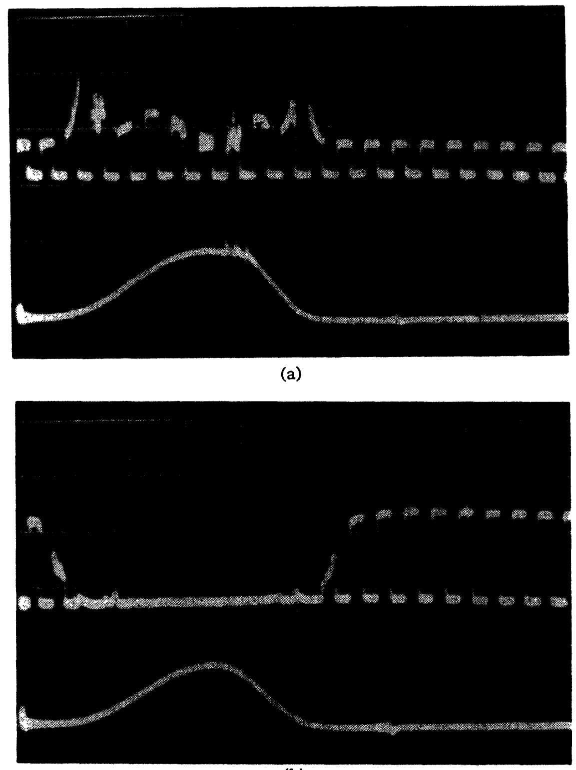


FIG. 4. Oscillograms showing (a) microwave signals transmitting through a plasma parallel to the magnetic field and (b) microwave signals attenuated by a plasma. In both (a) and (b) the lower trace is the current through the discharge.

Experimental Results

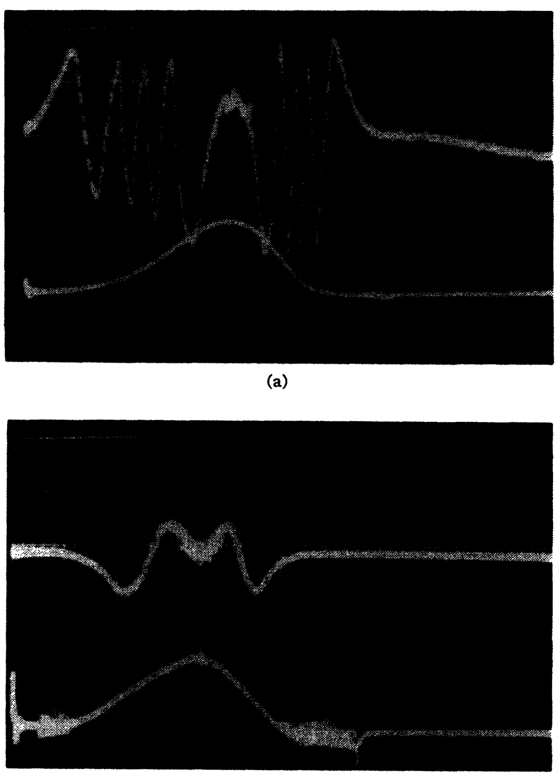
Measurements were made to locate the regions of transmission and attenuation and the associated resonances and cutoffs, as indicated in Fig. 1.

The magnetic field direction was chosen to give either the r or l mode as desired. The magnetic field strength was measured and hence ω_c was known. The microwave frequency was set as desired, determining the position along the β^2 axis of Fig. 1. During the discharge pulse the amplitude of the signal, after transmission through the plasma, was compared with the amplitude of the signal transmitted in the absence of the plasma.

Figures 4(a) and (b) show typical responses for transmission measurements. Time is increasing from left to right (1 cm/msec) and in each case the lower trace is the current through the discharge and the upper trace is the modulation envelope of the microwave signal, presented on a logarithmic scale. The plasma-free transmission amplitude may be seen at the right-hand end of these traces after the discharge has been extinguished. In (a) there is essentially no attenuation of the signal during the presence of the plasma, while in (b) there is over 25 dB of attenuation at peak current. Figures 4(a) and 4(b) are typical of regions of transmission and attenuation, respectively.

The l mode was investigated for $\beta^2 > 1$, that is, above the horizontal line in Fig. 1. It was found that transmission occurred for all currents below a critical current and, at higher currents, severe attenuation was present. Since we know from later measurements that, as the current through the discharge is increased, the electron density is increased, the onset of attenuation must correspond to crossing the parabola in Fig. 1. However, when the magnetic field was reversed, the r mode was present and it was found to transmit freely for all attainable values of the current. This indicates that, at high currents, the r mode was propagating at frequencies less than ω_p, which is the "whistler" mode.

On increasing the microwave frequency so that $\beta^2 < 1$, that is, below the horizontal line in Fig. 1, it was found that the r mode would transmit only at very low values of the discharge current. The transition between the regions of transmission and attenuation must correspond to crossing the left-hand branch of the parabola in Fig. 1. For the l mode with $\beta^2 < 1$, however, transmission was found to occur for higher currents but there was still a transition to attenuation. This presumably corresponds to crossing the right-hand branch of the parabola in Fig. 1.



(a)

(b)

FIG. 5. Oscillograms showing interferometer response for (a) right-hand circularly polarized microwave signals propagating through a plasma parallel to the magnetic field and for (b) left-hand circularly polarized microwave signals. In both (a) and (b) the lower trace is the current through the discharge.

The above few paragraphs show how the various regions of the β^2-α^2 plane were located and the transitions from one to the other found. The remainder of this section describes the quantitative measurements which were made on the various transitions and the refractive indices, from which electron densities were calculated.

Figures 5(a) and (b) show typical interferometer responses for the r and l modes, respectively, both with a frequency such that $\beta^2 > 1$. The change from one mode to the other was made by reversing the magnetic field direction. Several interesting features of these curves are noticeable. In both (a) and (b) the maximum phase change and consequently maximum density occurs at almost the same time as peak current. Also, the interferometer response trace initially moves away from the null position in opposite directions in (a) and (b) of Fig. 5, indicating that in one case the refractive index becomes greater than unity and in the other case becomes less than unity. The interferometer response showed that the r mode had the larger refractive index, as expected from Fig. 1.

Most of the measurements described below were made at a gas pressure of 15 μ, and a magnetic field strength of 3570 G, giving an electron cyclotron frequency of almost exactly 10^{10} cps.

The first mode for which interferometer measurements are described is the r mode with $\beta^2 < 1$, that is the mode in the bottom left-hand corner of Fig. 1. The microwave frequencies used were 10.6×10^9 and 11.2×10^9 cps, giving values for β^2 of 0.89 and 0.80. The refractive index was measured at peak current during the pulse for several values of the peak current, and the average electron density was calculated using Eq. (3), assuming that the refractive index varied little along a wavelength between the antennas. For this mode the refractive index should always be less than unity and this was found to be true.

The results of these measurements are shown in Fig. 6 as graphs of electron density vs peak current. The points marked with triangles represent the densities measured using the 11.2×10^9 cps signal. The cutoff density for this mode is shown. The points plotted with black dots were obtained using the 10.6×10^9 cps signal. The cutoff density for this mode is also shown. These cutoff densities represent the densities at which the left-hand branch of the parabola in Fig. 1 is crossed. It may be seen that densities measured using the different frequencies are in reasonable agreement with each other.

The highest density measured with each frequency is considerably less than the cutoff density for that frequency. This is because the density along the microwave path was not uniform. The highest density point plotted represents the highest current which could be used without causing severe attenuation of the signal. At the average density indicated by the highest point there must then exist, at some point in the discharge, a region of plasma with a density equal to the cutoff

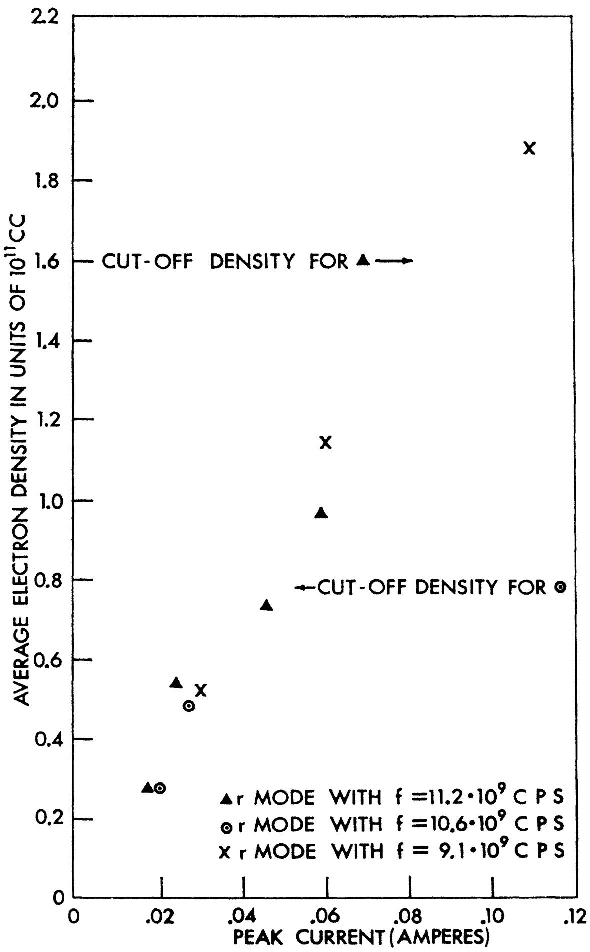


FIG. 6. Graph of electron density, measured by microwave interferometer operating in various propagation modes, vs peak current through the discharge.

density for that frequency. This means that information is obtained about the average density and the peak density of the plasma and consequently a density profile can be estimated. The ratio of peak to average densities measured by the 10.6×10^9 cps signal was 1.59 and by the 11.2×10^9 cps signal was 1.65. It was found that the calculated peak to average density ratio was roughly the same regardless of the type of density profile assumed along the axis, provided some reasonable profile was taken—cosine, cosine^2, Gaussian, or zero-order Bessel function. For the measurements described in this paper, it was usually regarded as sufficient to multiply the values of the average density given in the graphs by 1.6 to give the peak density.

In Fig. 6 the points marked with crosses represent the average density as measured using the r mode with a frequency of 9.1×10^9 cps. This gives a value of $\beta^2=1.21$ corresponding to the r mode above the horizontal line in Fig. 1. This mode has no high-density cutoff. The interferometer response for this mode indicated, as expected, that the refractive index was greater than unity. The densities measured using this mode are in good agreement with those measured using the other r modes.

Figure 7 shows further density measurements made using different propagation modes. Some of the results shown in Fig. 6 are duplicated here to provide continuity. The triangles are the same as those plotted in Fig. 6. The crosses are again the same as in Fig. 6 but are here continued to densities approximately equal to 10^{12} electrons/cc, which occurred at a peak current of approximately 1.2 A. It was found to be impossible to go to higher currents (or densities) because at this current an instability occurred in the discharge which made further measurements of phase, using propagation along the field lines, almost meaningless. The points plotted with circles represent measurements made using the l mode with a frequency of 9.1×10^9 cps. The densities measured in this way may be seen to be in good agreement with those measured using the r mode

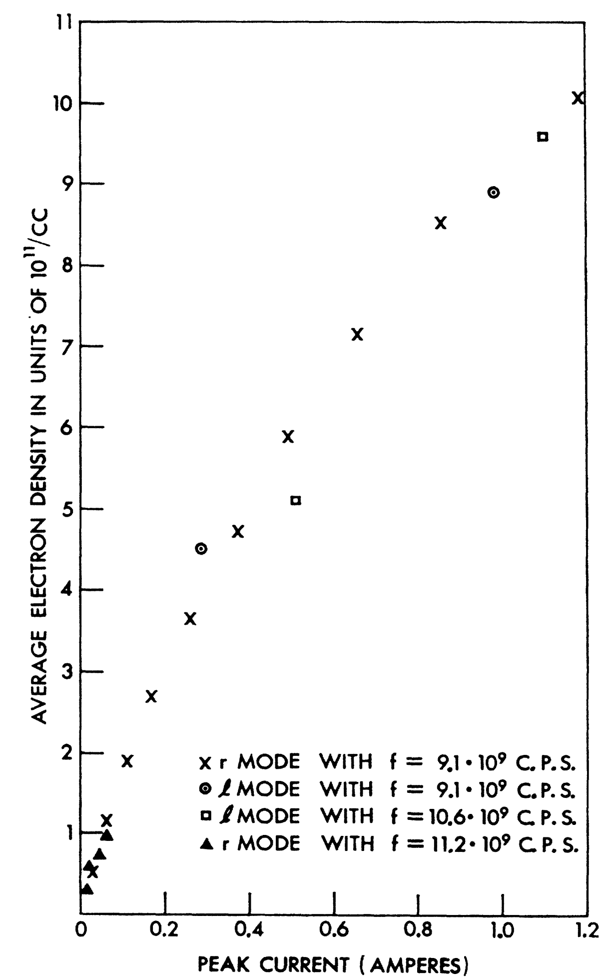


FIG. 7. Graph of electron density, measured by microwave interferometer operating in various propagation modes, vs peak current through the discharge.

at the same frequency. The points plotted with squares in Fig. 7 represent densities measured using the l mode with a frequency of 10.6×10^9 cps, which is below the horizontal line in Fig. 1. These points are again in reasonable agreement with the others plotted in Fig. 7. It should, however, be noted that there is a possibility of significant error in the measurements made using the l mode because the interferometer response was often irregular and because the rate of change of phase with current was much smaller for this mode than the r mode.

The highest values of density measured using the r mode were approximately 10^{12} electrons/cc. The associated plasma frequency was then approximately equal to 9×10^9 cps, which is about the same as the signal frequency. However, the density of 10^{12} electrons/cc is an average density and, using the figures given earlier, should be multiplied by 1.6 to obtain the peak density. This gives a value for the peak density of approximately 1.6×10^{12} electrons/cc and indicates that propagation was occurring in the "whistler" mode, $\alpha^2>1$. Measurements of a different type described later support this belief.

Unfortunately, it was not possible to make phase measurements of this type at higher currents. The onset of the instability, mentioned earlier, meant that phase measurements on signals propagating along the magnetic field lines could no longer be made. However, it was still possible to determine whether a particular mode was transmitting or being attenuated as described earlier [Fig. 4(a) and (b)]. Streak photography of the plasma column when the instability was present showed that the column had constricted to about one-third of its normal diameter and moved erratically about the discharge tube.

Semiquantitative measurements of the electron density were made at higher currents, when the instability was present, by propagating higher frequency microwave signals across the plasma column perpendicular to the direction of the steady magnetic field.

The microwave frequency used was in the neighborhood of 35.0×10^9 cps and the orientation of the waveguide was such that the electric vector was polarized parallel to the steady magnetic field. Under these conditions the plasma reacts as though no steady magnetic field were present and Eq. (1) may be applied.

The electron density required to give a plasma frequency equal to 35.0×10^9 cps is approximately 1.6×10^{13} electrons/cc and, even at 10 A peak current, the microwave signal was not cut off, indicating that densities greater than 1.6×10^{13} electrons/cc were never obtained.

In the density range covered by the measurements shown in Figs. 6 and 7 the density was normally too low to be measured using the 35.0×10^9 cps microwaves.

In the region in which the instability was present the measurements cannot be considered very accurate, both because of the presence of the instability and because of the fact that the microwave signal was not cut off. Thus, no experimental information could be obtained about the density profile perpendicular to the magnetic field. The densities quoted here were calculated assuming that the density was uniform across the plasma column.

At 1.5 A peak current the average density was 1.5×10^{12} electrons/cc and, if one is entitled to multiply by 1.6 to give the peak density, a value of 2.4×10^{12} electrons/cc is obtained. At approximately 1.5 A the l modes with frequencies of 8.9, 9.1, 10.6, and 11.2×10^9 cps became attenuated. This may correspond to crossing the right-hand branch of the parabola in Fig. 1. It can be seen from Fig. 1 or Eq. (3) that this should occur at about $\alpha^2\approx2$, that is a maximum density of approximately 2×10^{12} electrons/cc and this figure can be compared with the above-measured density of 2.4×10^{12} electrons/cc.

As the peak current through the discharge tube was increased from 1.5 A to its maximum value of 10 A, the average electron density as measured by the 35.0×10^9 cps microwaves increased from 1.5×10^{12} electrons/cc to 7.0×10^{12} electrons/cc. With the high currents and densities, i.e., above 1.5×10^{12} electrons/cc the l mode could not be transmitted through the plasma at any of the four frequencies listed. Using the r mode, however, transmission was found to occur at all currents for the 8.9 and 9.1×10^9 cps signals but not for the 10.6 and 11.2×10^9 cps signals. In other words, transmission occurred for the r mode with $\beta^2>1$ but not with $\beta^2<1$. The transmission must therefore be occurring in the "whistler" mode as shown in the top right-hand corner of Fig. 1.

Summarizing then, measurements were made on the refractive index and hence electron density using four different propagation modes as indicated in Fig. 1 for $\alpha^2<1$. The electron densities measured using these modes were in good agreement with each other. At higher densities, i.e., for $\alpha^2>1$, the transmission and attenuation characteristics of modes shown in Fig. 1 were measured; and, using densities measured by microwave propagation perpendicular to the magnetic field, it was shown that the cutoffs for the l modes were in reasonable agreement with those predicted.

HIGH-TEMPERATURE SECTION

Drummond[4] has investigated the effect of nonzero electron temperature on the complex microwave conductivity tensor for a plasma in a magnetic field. In this report most interest is attached to the transmission and attenuation characteristics of the "whistler" mode of propagation.

In the case of zero temperature the transmission characteristics can be studied by investigating Eq. (3) which, if $\alpha^2>1$, indicates complete transmission when $\beta^2>1$ and complete reflection when $\beta^2<1$.

Drummond has shown that one effect of a nonzero electron temperature is that the refractive index is no longer purely real or purely imaginary but is complex and consequently, the plasma absorbs microwave power. Another feature is that the imaginary part of the refractive index now appears at microwave frequencies less than the electron cyclotron frequency ω_c. This means that attenuation will occur at frequencies below ω_c and the effect is similar to a decrease in ω_c. He has shown that the shift in the onset of attenuation from ω_c is greater for greater values of α^2, that is, for greater values of the electron density and also increases with temperature. A linear approximation was made, which shows that the important quantity is neither n, the electron density, not T, the electron temperature, but is the product of the two. Figure 8 shows the transition frequency from transmission to attenuation as a function of this product, in terms of the quantity $8\pi nkT/H^2$, where k is Boltzmann's constant and H is the magnetic field strength. This quantity, $8\pi nkT/H^2$, which we will identify by γ,[7] is the ratio of electron kinetic pressure to magnetic field pressure, and is an important quantity in the consideration of "thermonuclear" plasmas.

An understanding of how such a shift in frequency occurs may be obtained from the following model. At frequencies near to, but just below ω_c, the refractive index becomes large [see Eq. (3)]. This means that the microwave phase velocity is very small and may be

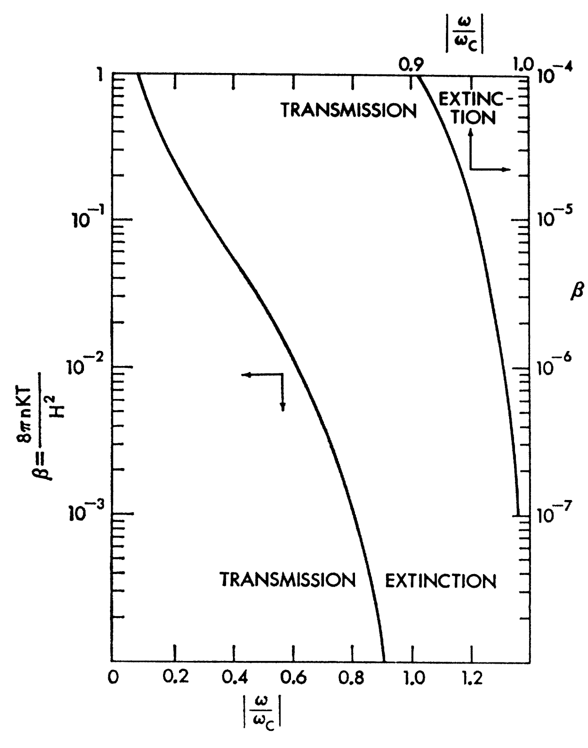


FIG. 8. "Crossover" frequency for right-hand circularly polarized microwave signals propagating parallel to the magnetic field in a plasma (after Drummond).

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[7] The quantity $8\pi nkT/H^2$ is usually identified by β but to avoid confusion with previous use of this symbol we will here use γ.

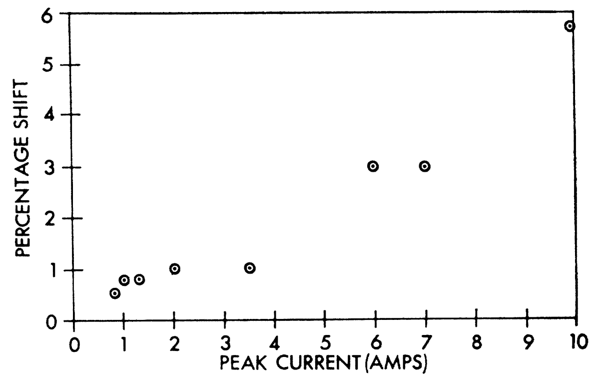

FIG. 9. Graph of percentage shift in electron cyclotron cutoff frequency for right-hand circularly polarized microwaves propagating parallel to the magnetic field vs peak current through the discharge.

comparable with the electron thermal velocities. Consequently, an electron moving in a direction opposite to the direction of the microwave propagation may see an appreciably Doppler-shifted microwave frequency. Thus a microwave frequency which, in the laboratory frame of reference, is less than ω_c, may appear in the electron frame of reference to be above ω_c. It is obvious that the Doppler shift would increase as the electron temperature increases. The shift will also increase as the electron density increases, since, as may be seen from Eq. (3), the higher values of the density produce higher values of refractive index and consequently lower microwave phase velocities.

The experiments described in this section were designed to test this theory. The technique employed was to measure the attenuation and transmission characteristics at peak values of discharge current as a function of microwave frequency. On the zero temperature picture there should be little or no attenuation at frequencies below the cyclotron frequency, and an abrupt cutoff at the cyclotron frequency. One would, however, expect to find, on the basis of the nonzero temperature theory, that the cutoff would be moved to lower frequencies. This was found to be the case.

At each peak current the microwave power transmitted through the plasma was compared with the power transmitted through the discharge tube when no plasma was present. The cutoff frequency was defined as the frequency at which the power transmitted through the plasma was down 10 dB, that is, 1% transmission. The downward shift of the cutoff frequency from ω_c was expressed as a percentage of ω_c. Figure 9 is a graph of the percentage shift versus peak current. The shift increases with the peak current. It is reasonable to suppose that the electron temperature would not decrease as the peak current through the discharge is increased and, since we know that the density increases as the current increases (from the measurements described in the previous section) we can state that, as γ

increases, the shift increases. This is as predicted by the theory.

It should be noted that the value of 1% transmission used to plot Fig. 9 was arbitrarily chosen and that any other reasonable transmission level could also have been used, resulting in a graph having the same shape as Fig. 9. It is difficult to define the cutoff point satisfactorily, for several reasons. Firstly, the experiment is sensitive to very small values of the imaginary part of the refractive index, and for these values, the linear approximation used in plotting Fig. 8 may not be valid. Secondly, the percentage transmission vs frequency response of the plasma is very irregular. This contributes largely to the difficulty, particularly at low currents, where the frequency range over which the change from 100% transmission to zero transmission occurs is comparable with or larger than the frequency shift shown in Fig. 9.

Although the above considerations do not affect the results qualitatively, they produce severe difficulties in applying a quantitative test to the theory. Nevertheless, using the cutoff as defined for Fig. 9, the smallest shifts indicate a value for γ of 10^{-7}, and at larger currents, a value of 10^{-5}. This gives a series of values for the product nT and, using the measured values of n from the previous section, values for T may be obtained. At the highest currents a value for T of 10 000°K is obtained but, as the current is decreased, the calculated value of T decreases, until, at the lowest currents, a figure of only a few hundred degrees is obtained. One would certainly expect, in a discharge of this type, that the electron temperature would not be so low. However, it is at these lower currents that the difficulty in applying a quantitative test is greatest and errors are most likely.

It must be recognized that the plasma is diamagnetic and this would tend to lower the electron cyclotron frequency. However, the magnitude of this effect would be of the order of γ and is three orders of magnitude too low to account for the effects described above. The shift in cutoff frequency is also larger, by at least one order of magnitude, than any reasonably estimated collision frequency. However, there is an indication that it is less than is predicted by the Drummond theory.

CONCLUSION

The technique of propagating microwave signals along the magnetic field lines may prove to be a useful diagnostic tool for high-density plasmas because of the transmission window at frequencies below the plasma frequency and the very dispersive nature of the plasma at frequencies close to the electron cyclotron frequency.

The technique suggests a possible solution to the problem of communication through the plasma sheath surrounding a space vehicle on re-entry, by introducing a magnetic field and propagating in the "whistler" mode. A further interesting speculation is on the possibility of finding a transmission window through solids.[8]

ACKNOWLEDGMENTS

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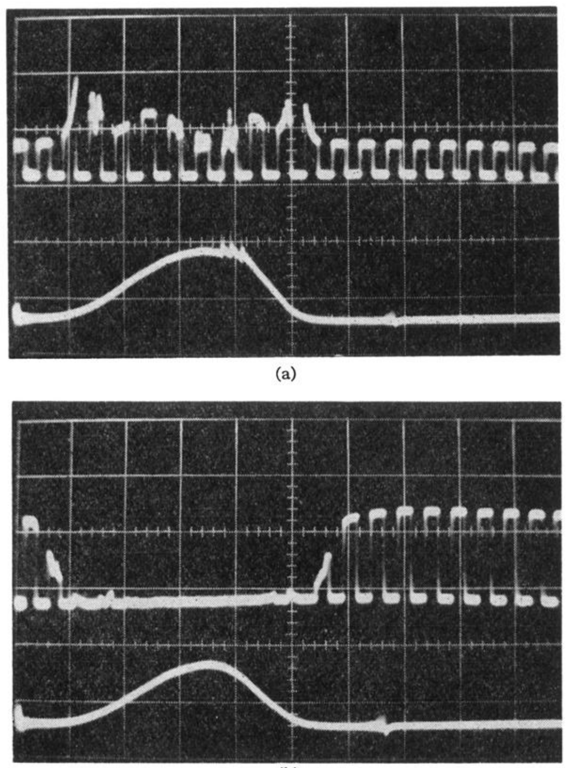
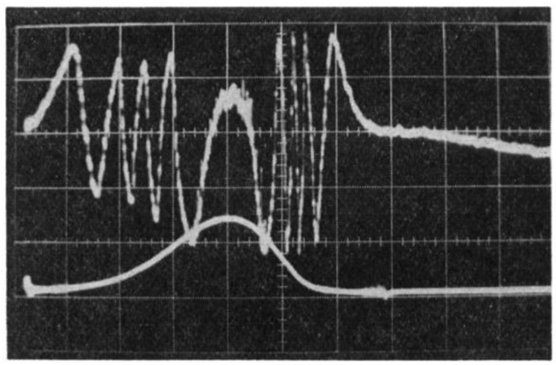
[8] O. F. Konstantinov and V. I. Perel, Soviet Phys.—JETP **11**, 117 (1960).

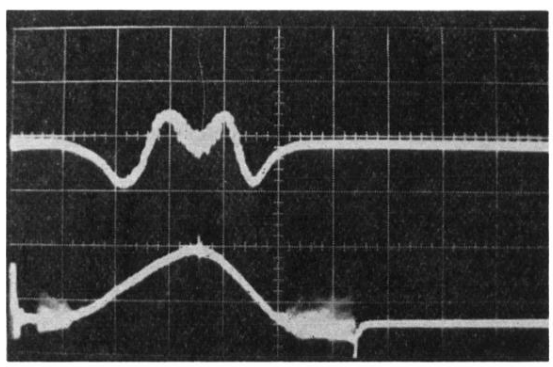


(a) (b)

FIG. 4. Oscillograms showing (a) microwave signals transmitting through a plasma parallel to the magnetic field and (b) microwave signals attenuated by a plasma. In both (a) and (b) the lower trace is the current through the discharge.



(a)



(b)

FIG. 5. Oscillograms showing interferometer response for (a) right-hand circularly polarized microwave signals propagating through a plasma parallel to the magnetic field and for (b) left-hand circularly polarized microwave signals. In both (a) and (b) the lower trace is the current through the discharge.