2.1: MICROWAVE PROPAGATION IN AN OVERDENSE BOUNDED MAGNETOPLASMA

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The magneto-ionic theory [1] shows that for plane wave propagation along the direction of the magnetic field in a magnetoplasma a mode of propagation exists when the frequency of the wave is smaller than the electron gyrofrequency of the medium. Electromagnetic waves will propagate in this mode regardless of the magnitude of the plasma frequency. It requires only that the collision frequency of the electrons in the plasma be sufficiently small so that collision damping does not excessively attenuate the waves. This mode of propagation has been used to explain very low frequency "whistles" associated with lightning discharges [2] and very low frequency emissions in the earth's exosphere[3]. It has been called the "whistler mode" by ionosphere physicists. For propagation in the whistler mode, a dense plasma has a large refractive index, is highly dispersive, and is highly anisotropic. In this paper experiments are described which attempted to use the properties of this mode of propagation as a diagnostic tool in the hot plasma of the magnetic field stabilized pinch discharges in ZETA [4]. The ZETA discharge tube is of toroidal shape with a 1-meter bore and a 3-meter mean diameter. Because of its large size, plane wave propagation through the plasma was considered to be feasible, and hence, the whistler mode theory applicable to the experiment.

While the experiments succeeded in demonstrating that electromagnetic waves could be made to propagate through the overdense plasma the detected signals exhibited properties that could not be completely accounted for in terms of the whistler mode theory. Further, wave propagation was detected which in no way could be explained by the theory. Analysis shows that the whistler mode properties result from the infinite plane wave solution to the wave equations. In a bounded plasma whose dimensions are large compared with the wavelength in the medium, propagation modes exist for which the infinite plane wave solution is a valid approximation. Other modes, however, are also allowed which, if excited, can contribute significantly to the actual fields.

To determine the nature of these modes numerical solutions to a coupled pair of second order linear differential equations, were required, subject, in the usual way, to the boundary conditions appropriate to the experimental arrangement. The method of solution of the coupled wave equations was first developed by Kales [5] in connection with the problem of ferrites in cylindrical waveguide, and extended by Van Trier [6] and others. These solutions show that a large number of discrete modes are allowed.

Figures 1 and 2 show some of the results for the circularly symmetric modes when ω_p/ω_H is 10, and when the plasma partially fills the guide. Figure 1 shows a plot of the (normalized) propagation constant, μ, as a function of ω/ω_H for the range $0<\omega/\omega_H<1.0$ and $\mu>10$. The whistler mode solution, shown by the dashed curve, is included for reference. In the range $0.5<\omega/\omega_H<1.0$, a large number of solutions appear with values of μ that are always greater than the propagation constant derived through the whistler mode theory. The modes retain much of the shape of the whistler mode solution and the density of modes is very great. The mode order number is given across the top of the figure. The mode structure in the region $\omega/\omega_H<0.5$ was not studied in detail since information regarding the behavior of the solution for low frequencies was not required for

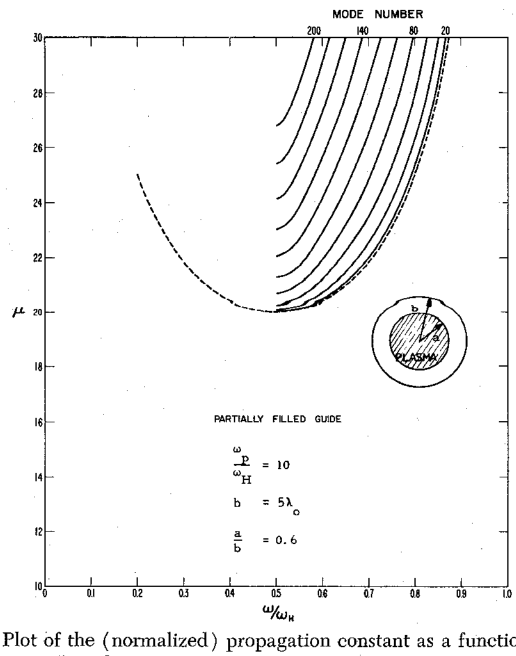

Fig. 1. Plot of the (normalized) propagation constant as a function of ω/ω_H for the "dispersive" modes in the partially filled guide.

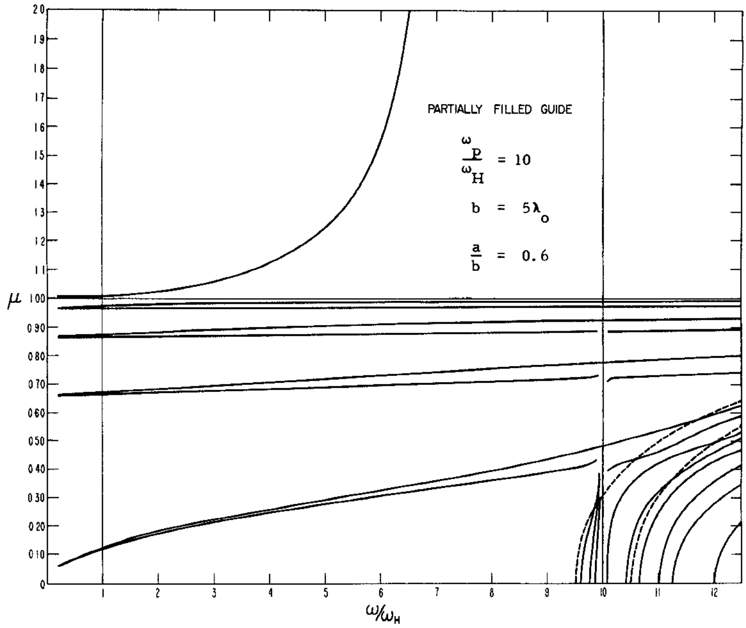

Fig. 2. Plot of the (normalized) propagation constant as a function of ω/ω_H for $0 < \omega/\omega_H < 12.5$ in the partially filled guide.

this experiment, although the mode structure is much more complex in this region than in the region $\omega/\omega_H > 0.5$. Since the propagation constants of the modes shown have a strong dependence on frequency, these may be called the "dispersive" modes.

Figure 2 shows the plot for the same conditions of the range $0 < \omega/\omega_H < 12.5$ and $\mu < 2.0$. The plane wave solutions, included for comparison purposes, are shown by the dashed curves. Of particular importance are the modes that appear over the whole gamut of frequencies for values of μ less than unity. Since the propagation constant of these modes exhibit little variation with frequency, these may be called the "non-dispersive" modes. In addition to these modes, other modes appear for ω/ω_H near 10, i.e., when the frequency of the wave begins to exceed the plasma frequency of the medium. Finally, an isolated mode, with μ greater than unity, appears in the range $0.2 < \omega/\omega_H < 7.0$. This mode and the "non-dispersive" modes disappear when the dimensions of plasma are allowed to increase so that the plasma column fills the guide, so that, for the plasma filled guide, a "stop" band exists over the range $\omega_H < \omega < \omega_p$.

All the qualitative features of the experimental data can be easily explained in terms of these modes. ZETA is basically a large pulse transformer in which the deuterium gas in the torus acts as the secondary of the transformer, and in which currents of several hundred kiloamperes are generated when a high energy condenser bank is discharged through the primary of the transformer. The purpose of this high current is to heat the gas to a high temperature and to force the gas to separate from the walls of the container in accordance with the famous "Bennett Relation" [7]. This process is known as the pinch effect. An axial magnetic field of several hundred gauss is generated by separate current carrying windings to help stabilize the pinch. Magnetohydrodynamic considerations show that when a magnetic field permeates a medium of high conductivity, the magnetic field lines are carried along with the motion of the medium. Therefore, when the current channel pinches, the axial magnetic field is compressed and the field intensity is increased.

Figure 3 is a typical example of the data obtained using 10-cm waves transmitted through ZETA plasma. The upper trace shows the detected signal. The lower trace shows the plasma current. This display can be interpreted as follows:

Shortly after the beginning of the preionization pulse the transmission is cut off when the plasma frequency equals the wave frequency. Since the plasma is presumed to fill the cylinder, the conditions are such that the plasma is in the "stop" region. With the onset of the high energy pulse, the plasma begins to pinch and the "non-dispersive" modes, similar to those in Figure 2, are excited as the plasma separates from the walls of the torus. Near the peak of the current pulse, the pinch is strongly developed and has compressed the axial magnetic field sufficiently so

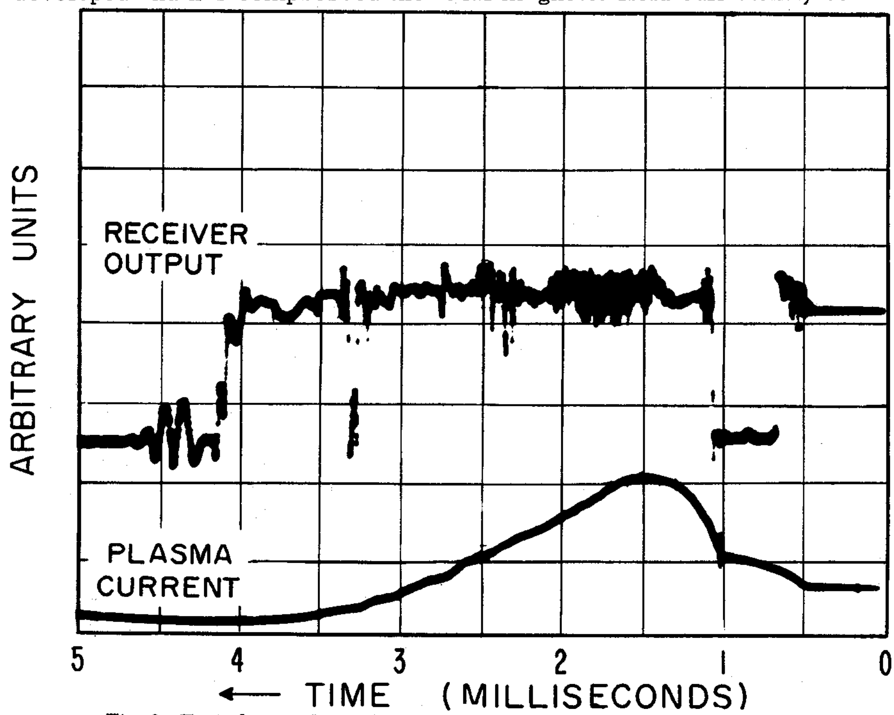

Fig. 3. Typical example of the signal transmitted through the ZETA plasma.

that "dispersive" modes, similar to those of Figure 1, are excited. The rapid variation in amplitude starting near the current maximum corresponds to new "dispersive" modes being excited in rapid order. These tend to phase interfere with each other (and with the "non-dispersive" modes) in a way that accounts for the rapid variation in signal amplitude. The current pulse now decays, and the pinched plasma column begins to expand. At approximately 2 milliseconds the gyrofrequency again passes the wave frequency and only the "non-dispersive" modes remain. These modes sustain the transmission until the plasma column again fills the torus. The transmission is then cut off until the electron density in the plasma decays sufficiently so that the plasma frequency is again less than the wave frequency. The process involved is quite complicated since not only are new modes excited as the pinch develops, but the propagation constants of the excited modes change as a result of the variation in both ω_H and ω_p during the pinch.

The conclusion, therefore, derived from the experimental results and the analysis developed to explain the results, is that the microwave signals transmitted through the dense ZETA plasma can be interpreted as the resultant of a multitude of discrete normal modes. The whistler mode, defined for our purposes as the infinite plane wave solution to the wave equations for frequencies smaller than the gyrofrequency, can exist in the ZETA plasma only as an approximation to some of the modes that are present but does not exist as a unique mode of propagation. Many of the normal modes have propagation characteristics generically related to the whistler mode, and propagation through an overdense plasma at frequencies below the gyrofrequency can be achieved.

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