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R. W. MOTLEY, S. BERNABEI,
W. M. HOOKE, R. MCWILLIAMS,
AND L. OLSON

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PLASMA PHYSICS LABORATORY

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PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

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Penetration of Slow Waves into an Overdense Plasma

R. W. Motley, S. Bernabei, W. M. Hooke, R. McWilliams, and L. Olson
Plasma Physics Laboratory, Princeton University,
Princeton, New Jersey 08540

ABSTRACT

We report probe measurements of the propagation of a 2.45 GHz slow wave launched into a linear, overdense test plasma by a phased double waveguide. We find that waves in the frequency interval $\omega_{LH} < \omega < \omega_{pe}$ penetrate to the plasma interior only if they satisfy the accessibility criterion.

I. Introduction

It has been suggested that toroidal fusion reactors may be heated by irradiation with high power rf beams at a frequency at or above the lower hybrid frequency $\omega_{LH} = \omega_{pi}/(1 + \omega_{pe}^2/\omega_{ce}^2)^{1/2}$.[1] This method entails the excitation of electrostatic waves in the surface layers of the plasma and their propagation to the plasma core, where absorption will transfer most of the wave energy to particle motion.

Stix[2] and Golant[3] have shown that slow wave propagation to the lower hybrid resonance layer is possible only if the wavenumber along the magnetic field $n_\parallel = ck/\omega$ satisfied the accessibility criterion

$$n_\parallel^2 > 1 + \omega_{pe}^2/\omega_{ce}^2 \quad , \tag{1}$$

where ω_{pe} and ω_{ce} are the electron plasma and cyclotron frequencies at the hybrid resonance. The accessibility criterion is important because it establishes rigid limitations on the types of structures capable of exciting slow, penetrating lower hybrid waves. The most promising of these structures for a fusion reactor is the phased waveguide array proposed by Lallia[4] and analyzed theoretically by Brambilla.[5]

The dispersion characteristics of waves in the frequency interval between ω_{LH} and ω_{pe} are illustrated in Fig. 1. Waves propagating along the upper sectors of the loops are referred to as "slow" waves; along the lower sectors, as "fast" waves. A slow wave launched from the outside must first tunnel through the low density non-propagating region $(n_\perp^2 < 1)$ before it can propagate to the interior. Propagation inward to regions of higher density is possible until the wave encounters the vertical section of its loop. Here it may either reflect or convert to the fast mode. In either case there is a maximum density determined by both the axial wavenumber and the magnetic field beyond which no wave propagation is possible. Providing $\omega^2 >> \omega_{ci}\omega_{ce}$ this critical density n_* is given by[6]

$$\frac{n_*}{n_c} = \left[\frac{(n_{\parallel}^2 - 1)\ \omega_{ce}}{2n_{\parallel}\omega}\right]^2 + 1\ , \qquad (2)$$

where n_c is the normal cutoff density $(m\omega^2/4\pi e^2)$ for $n_{\parallel} = 0$. Equation (2) is more appropriate to our experimental conditions than Eq. (1), since no lower hybrid resonance may exist in our plasma. An alternative interpretation of Eq. (2) is that wave propagation to the plasma interior is allowed only if $\omega_{pe}/\omega_{ce} \lesssim (n_{\parallel}^2 - 1)/2n_{\parallel}$, i.e., for $\omega_{pe}/\omega_{ce} \lesssim 1$, if, as in our experiment, $n_{\parallel} = 2.5$. For a given waveguide phasing and plasma density there exists a critical magnetic field, $B_c \sim 3$ kG, below which wave propagation to the interior is not possible.

II. The Experiment

We have devised an experiment to check equation (2) for slow waves launched into an overdense plasma by a phased twin waveguide. The plasma source, described elsewhere,[7] is an rf-generated argon plasma column 2 m long and 10 cm in diameter, confined by a uniform magnetic field of < 16 kG. As shown in Fig. 2 the twin waveguide was positioned at the edge of the plasma column. The two waveguides were excited in the TE_{10} dominant mode $(E \| B_o)$ by a 20 W, 2.45 GHz magnetron. Typical transmission coefficients of 80 - 90% were achieved if the guides were excited out of phase, as described in previous papers.[8,9] The plasma column was overdense; typically, $n/n_c \sim 20 - 25$ $(n \sim 2 \times 10^{12} \text{cm}^{-3})$ at the column center. Waves generated by the exciter were studied with a triaxial probe moveable both axially and radially.

III. Wave Structure

Radial scans of the RF signal within the plasma column are shown in Fig. 3. If both plasma density and magnetic field were high, two radial peaks were observed, one on the plasma surface and the other in the interior. Radial scanning at increasing axial distances from the exciter showed that the surface waves do not penetrate the column: they evanesce radially over a distance of 1 - 2 cm. The body waves, on the other hand, move across the plasma column at an angle of ~ 15°, consistent with the angle expected from the resonance cone, $\theta \simeq \omega/\omega_{pe} \sim 0.2 - 0.25$.[10] Body waves were excited most efficiently if the waveguide phase was 180°; if the phasing was changed to 0°, as shown in Fig. 4, the reflected signal rose to ~ 50% of the input signal, and the wave amplitude within the resonance cone almost disappeared. This behavior is expected, since 180° phasing favors the excitation of short, penetrating waves, while 0° phasing favors the excitation of long wavelength, nonpenetrating waves.[5]

In general the wave structure in the "near field" of the antenna, i.e., within one or two free space wavelengths of the waveguide, appears to consist of the resonance cone and a surface wave that is concentrated near the plasma surface. Under some conditions the surface wave appears to spiral around the plasma column. Beyond this zone, in the region where the resonance cone emerges from the plasma, there exists a mixture of wave modes. Under certain conditions (e.g., high field) the dominant far field mode is a primarily cylindrical symmetric, standing electrostatic surface wave.

By means of an interferometer, in which the detected signal was mixed with a portion of the input signal, we have measured the radial and axial structure of both wave groups. We find that the surface waves (in the high field cases) are of long wavelength, $n_\parallel = 1 - 1.2$, as shown in Fig. 5, with no measurable phase change in the radial direction. The body waves are of short wavelength; $n_\parallel = 2 - 2.5$, as expected from the dimensions of the exciting waveguide, and $n_\perp = 9 - 12$. The ratio of $n_\perp/n_\parallel = 4 - 5$ is consistent with that expected from the approximate electrostatic dispersion relation $n_\perp/n_\parallel \tilde{=} \omega_{pe}/\omega = (n/n_c)^{1/2}$. The conclusion to be drawn from these measurements is that the long wavelength component of the spectrum excited by the twin waveguide is nonpenetrating, while the short wavelength waves cross the column at the expected cone angle. These conclusions are consistent with previous work.[8,9]

IV. Wave Penetration

According to Eq. (2), however, the short wavelength component may penetrate the surface only if the magnetic field is greater than a critical value B_c . For the conditions of our experiment $(n_\parallel \sim 2.2)$, $B_c \sim 3$ kG. We have investigated the structure of the rf field as a function of the magnetic field strength, holding the plasma density approximately constant. The results are shown in Fig. 6. As the field was reduced below ~ 3 kG, at which point $\omega_p^2/\omega_c^2 \sim 1$, the surface wave increased by a large factor, while the amplitude of the wave in the resonance cone decreased. The relative amplitude changed by a factor of ~ 7, as shown in Fig. 7. On the other hand, the reflection from the twin waveguide showed no appreciable change with magnetic field. Thus a significant fraction of power was diverted at low field from the body to the surface waves.

The existence of a critical magnetic field of ~ 3 kG is consistent with Eq. (2), as indicated in the Figure, since the twin waveguide excites a band of wavelengths extending from $n_\parallel = 1$ to $n_\parallel \lesssim 3$, according to Brambilla.[5] The pure surface wave generated in this low field regime has no measurable wavelength perpendicular to the magnetic field, but $n_\parallel \sim 2 - 2.8$ (Fig. 5). Thus we see that short wavelength waves insure surface penetration only if they satisfy Eq. (2). Additional measurements at varying electron densities showed that the critical field B_c increased with electron density.

Below $B \sim 1.8$ kG the wave excitation pattern changed once again, showing both a surface and a penetrating wave comparable in magnitude to the surface wave. Although we have not yet examined the penetrating wave in detail, we suspect that it is associated with the electron cyclotron frequency or a second harmonic $(\omega_c/\omega \lesssim 2)$.

In conclusion, we have shown that slow waves can penetrate an overdense plasma column only if the magnetic field exceeds a critical value consistent with the (modified) accessibility criterion. This criterion has formed the basis for the design of all lower hybrid slow wave structures to heat toroidal plasmas.

Acknowledgments

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FIGURE CAPTIONS

Fig. 1. Dispersion curves in the frequency interval $\omega_{LH} < \omega < \omega_{pe}$, for the case $\omega^2 > \omega_{ci}\omega_{ce}$; $n_\parallel = 2.2$.

Fig. 2. Coupling of waves to an overdense plasma column by means of a phased twin waveguide. The waveguide elements were each 5.8 x 2.0 cm (along the field) and were filled with teflon to lower the cutoff frequency. The trajectories of the excited waves were measured with a triaxial probe.

Fig. 3. Radial wave profiles measured with the triaxial probe 8 and 13 cm from the mouth of the waveguide; B = 6.5 kG, $n(o) = 1.6 \times 10^{12} cm^{-3}$.

Fig. 4. Density and wave profiles with in-(dashed line) and out of phase (solid line) excitation of the twin waveguide; B = 5.6 kG, $n(o) = 1.3 \times 10^{12} cm^{-3}$.

Fig. 5. Axial phase measurements of surface and interior waves with high and low magnetic fields. The intersecting curves were obtained by mixing the wave signal with a reference signal and then repeating the axial scan with the reference signal shifted in phase by 180°. The axial extent of the resonance cone at the plasma center (r = 0) is indicated by the double arrow.

Fig. 6. Radial profiles of wave amplitude taken 8 cm from the waveguide with different magnetic fields. The parameter ω_p^2/ω_c^2 was calculated from the measured plasma density and the magnetic field.

Fig. 7. Percentage of waveguide power transmitted to the plasma (upper curve) and the ratio of the surface wave signal to the interior wave signal as a function of magnetic field. The waveguide elements were excited out of phase

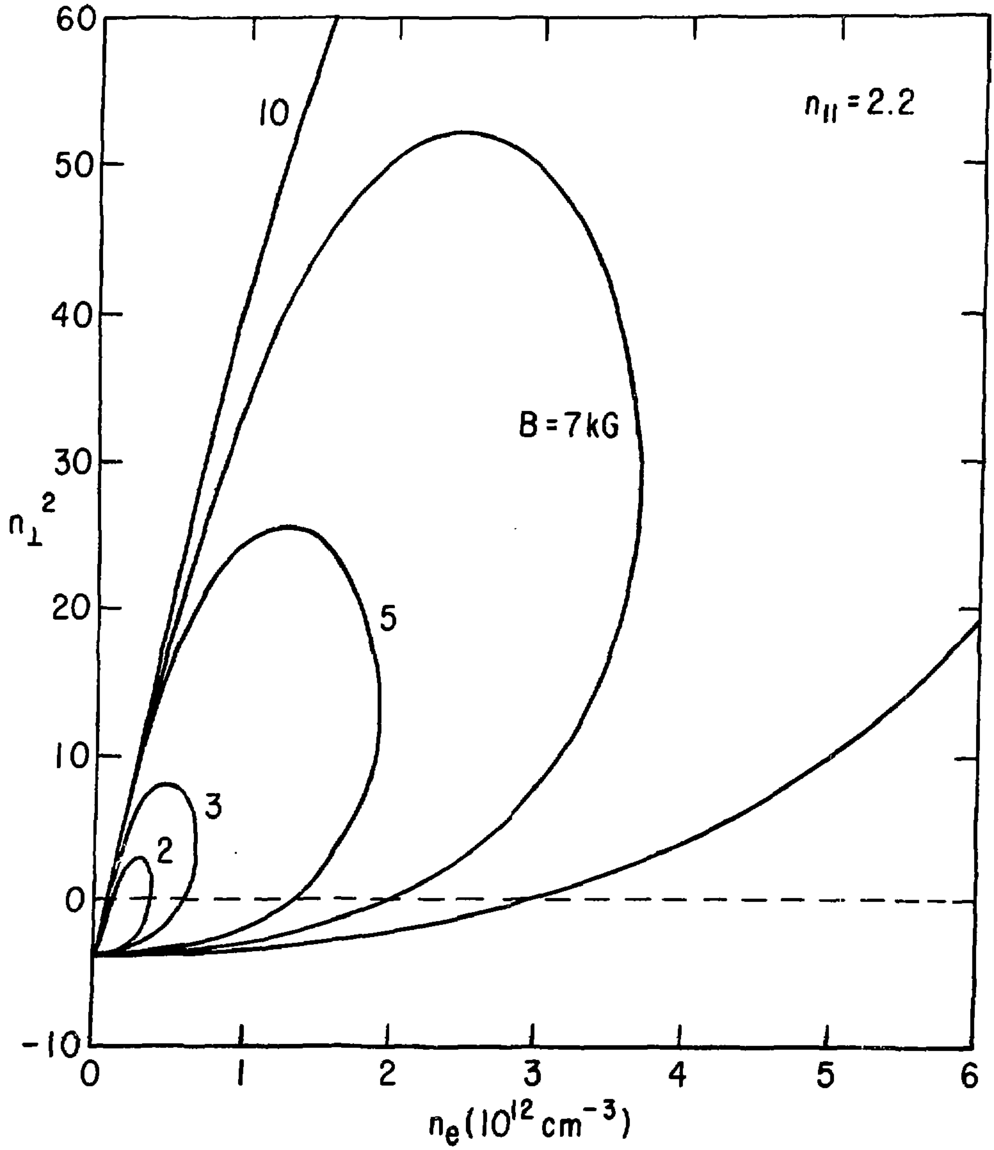
60
50
40
30
20
10
0
-10
$n_\perp^2$
0
1
2
3
4
5
6
$n_e(10^{12}\,cm^{-3})$
$n_\parallel = 2.2$
10
B = 7 kG
5
3
2

Fig. 1. 776229

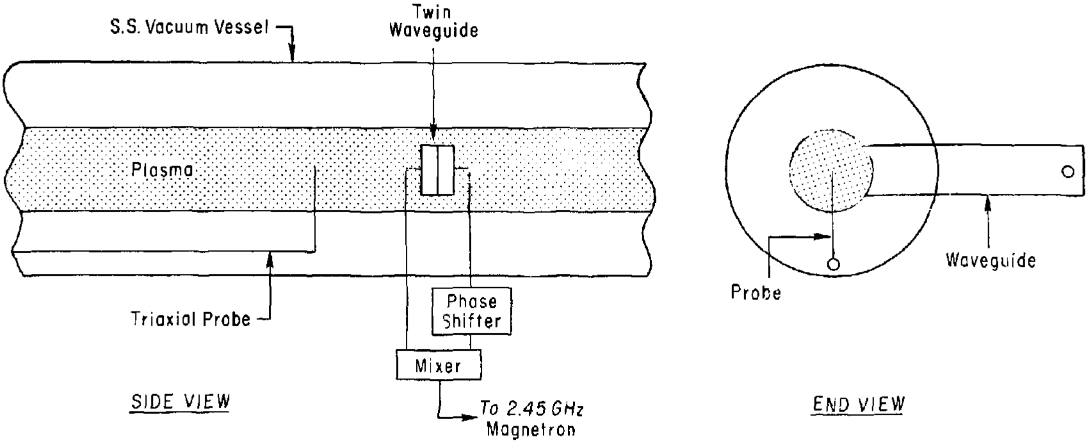
S.S. Vacuum Vessel
Twin Waveguide
Plasma
Triaxial Probe
Phase Shifter
Mixer
To 2.45 GHz Magnetron
SIDE VIEW
Probe
Waveguide
END VIEW

Fig. 2. 776231

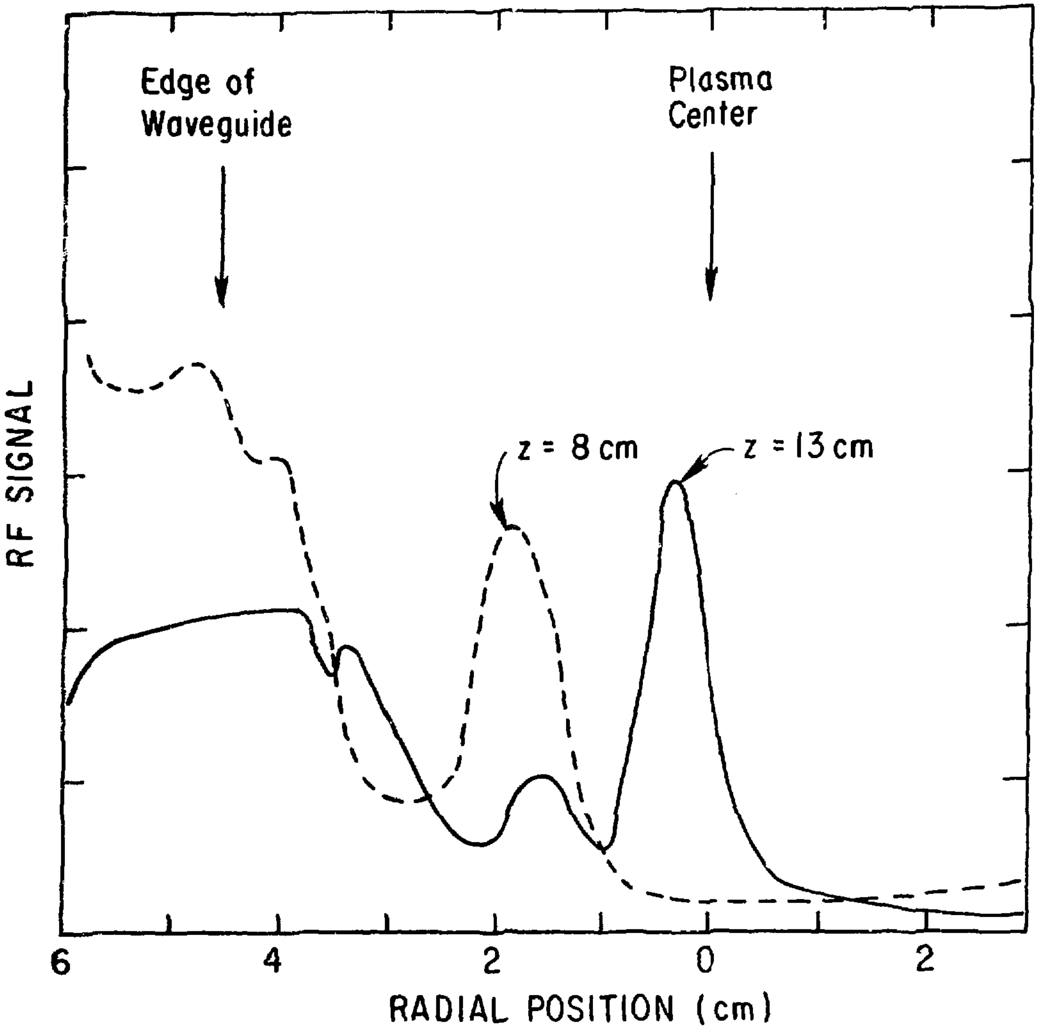
Edge of Waveguide
Plasma Center
z = 8 cm
z = 13 cm
RF SIGNAL
6
4
2
0
2
RADIAL POSITION (cm)

Fig. 3. 776226

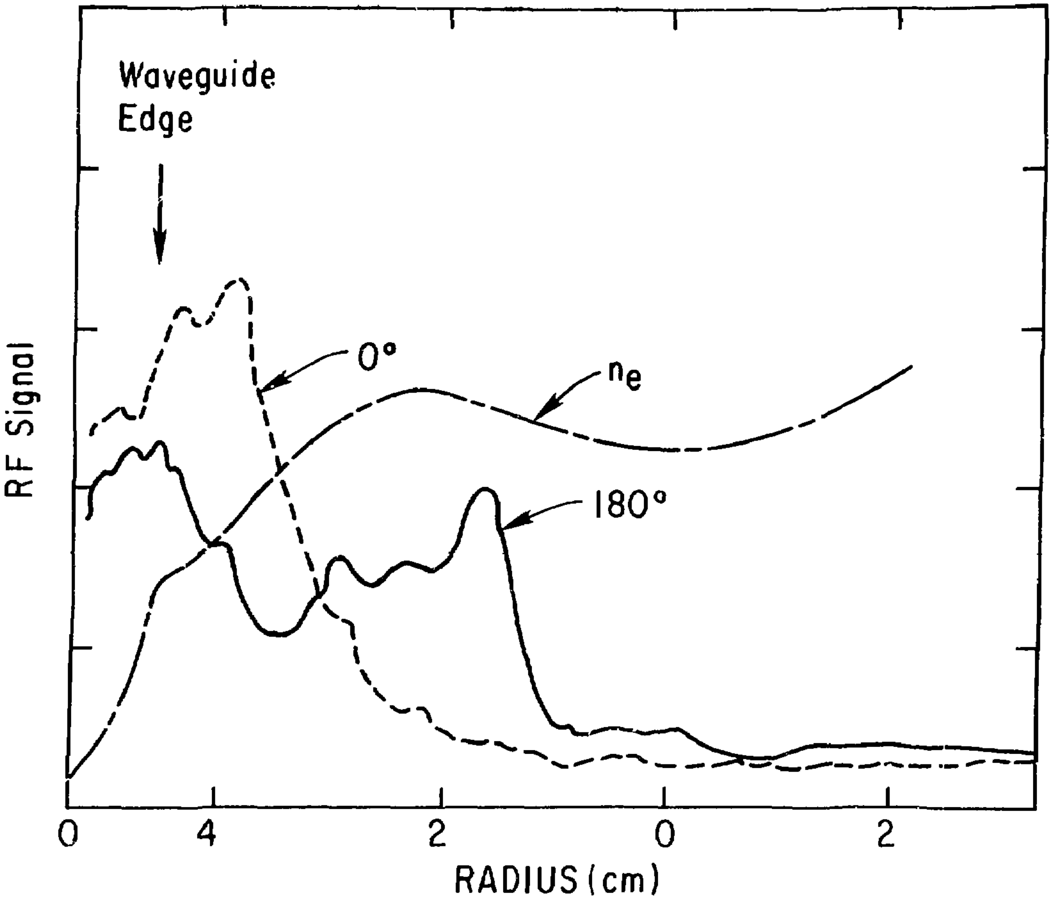

Fig. 4. 776230

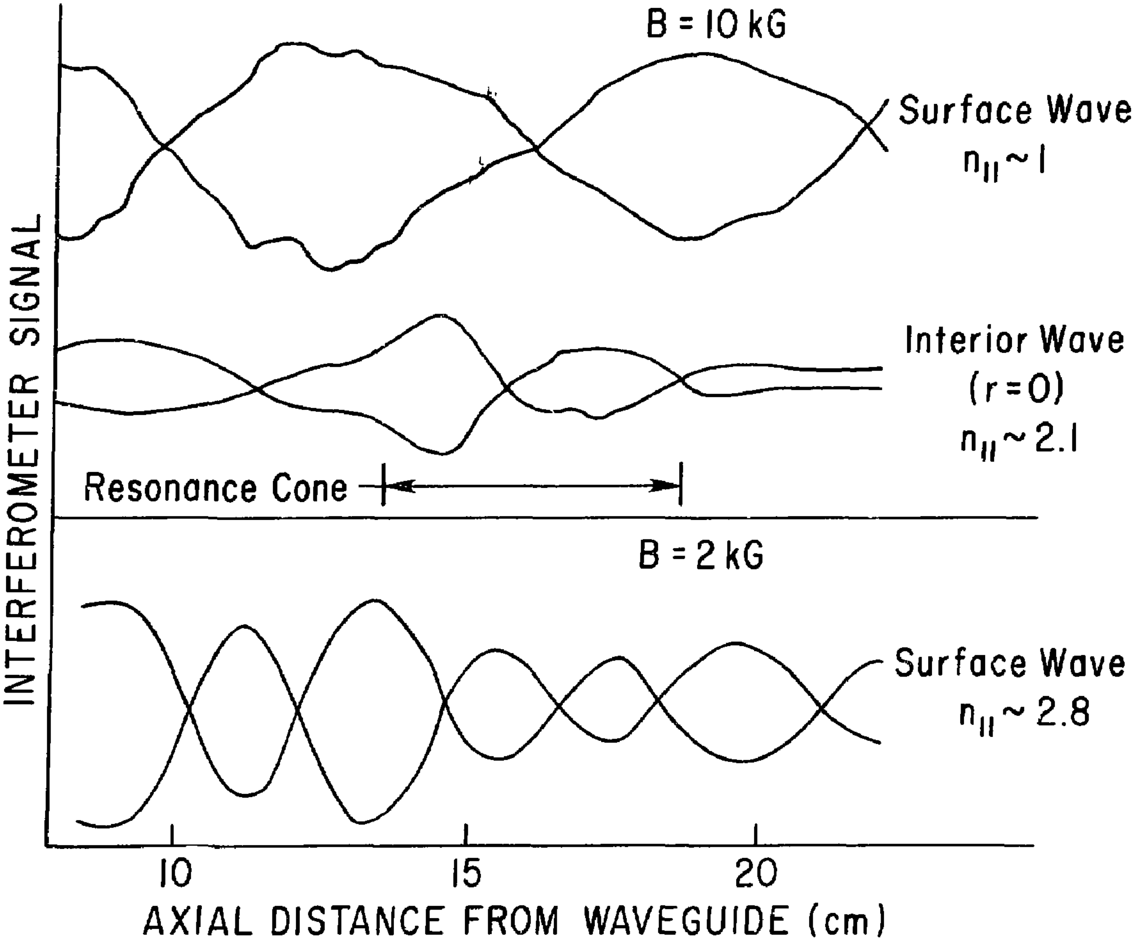
B = 10 kG
Surface Wave
$n_{\parallel} \sim 1$
Interior Wave
(r = 0)
$n_{\parallel} \sim 2.1$
Resonance Cone
B = 2 kG
Surface Wave
$n_{\parallel} \sim 2.8$
INTERFEROMETER SIGNAL
10
15
20
AXIAL DISTANCE FROM WAVEGUIDE (cm)

Fig. 5. 776227

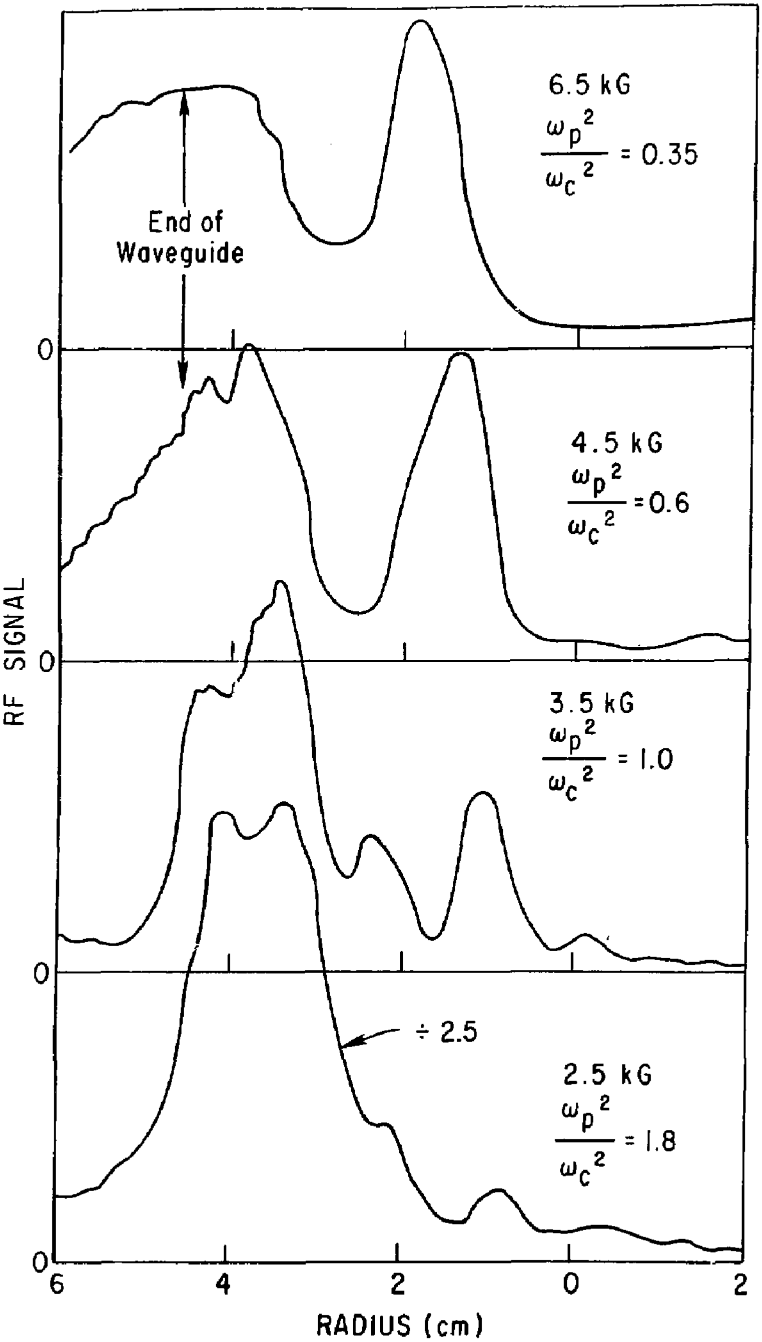
6.5 kG
$\frac{\omega_p^2}{\omega_c^2} = 0.35$
End of Waveguide
4.5 kG
$\frac{\omega_p^2}{\omega_c^2} = 0.6$
3.5 kG
$\frac{\omega_p^2}{\omega_c^2} = 1.0$
÷ 2.5
2.5 kG
$\frac{\omega_p^2}{\omega_c^2} = 1.8$
RF SIGNAL
0
0
0
0
6
4
2
0
2
RADIUS (cm)

Fig. 6. 776232

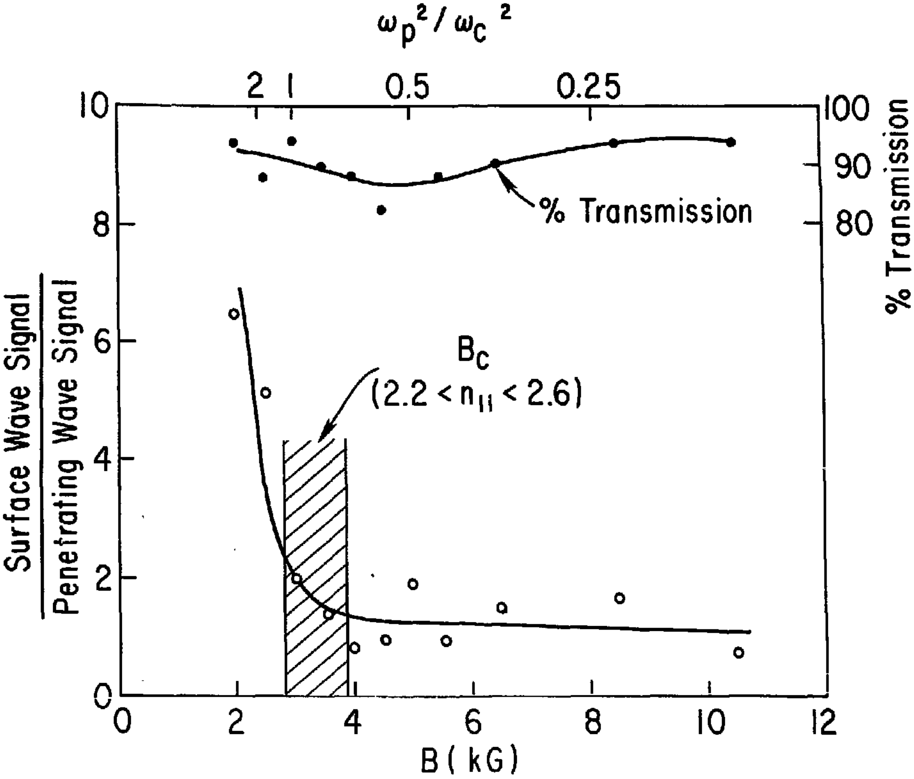
ω_p^2/ω_c^2
2
1
0.5
0.25
10
8
6
4
2
0
100
90
80
% Transmission
% Transmission
B_c
$(2.2 < n_{\parallel} < 2.6)$
Surface Wave Signal / Penetrating Wave Signal
0
2
4
6
8
10
12
B (kG)

Fig. 7. 783003