239
1-11-83
PPPL-1961

UC20-D,F,G

PPPL-1961

Dr. 1109

PPPL--1961

DE83 005051

RADIO-FREQUENCY WAVE TRAJECTORIES FOR
CURRENT DRIVE IN TOKAMAK REACTORS

By

MASTER

K.L. Wong and M. Ono

DECEMBER 1982

PLASMA
PHYSICS
LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CHO-3073.

DISTRIBUTION STATEMENT: UNCLASSIFIED

Radio-Frequency Wave Trajectories for Current Drive in Tokamak Reactors

King-Lap Wong and Masayuki Ono

Princeton Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

ABSTRACT

Detailed ray tracing calculations were carried out for three modes of waveguide-launched radio-frequency waves for tokamak reactor parameters to evaluate their applicability for steady state current drive. The merits and demerits of each mode are discussed.

DISCLAIMER

This document contains information that is the property of the U.S. Government and is being furnished to you under a license. It is to be used for the specific purposes for which it was provided and is not to be distributed outside your organization. It is to be destroyed when it is no longer needed for the specific purposes for which it was provided. It is not to be used for advertising or promotional purposes, for creating new products, or for any other unauthorized use. It is not to be used for the purpose of reproducing or transmitting information in any form or by any means, electronic or mechanical, including photocopying, recording, or by any information storage and retrieval system, without prior written permission from the U.S. Government.

I. Introduction

The success of lower hybrid wave current drive¹ has rapidly grown out of small experimental devices²⁻⁴ into large tokamaks,⁵⁻¹⁰ causing plasma current generation with radio-frequency waves to become one of the major topics in fusion research. This is primarily due to the strong interest in steady state tokamaks. Until recently, most of the current drive experiments have utilized lower hybrid waves. This trend has been prompted by readily available equipment originally planned for lower hybrid wave heating where the waveguide phase can be easily adjusted to launch an unidirectional wave. So far, they have been successful only in low density plasmas. It is well known that magnetized plasmas can support many modes of waves and their suitability for sustaining a steady state tokamak reactor can be expected to differ from mode to mode. The major advantages of lower hybrid waves consist of the all-metal waveguide coupler (phased waveguide arrays) and the relatively low wave frequency (≤ 10 GHz) so that multi-megawatt radio-frequency technology is already available without major development. These advantages are shared by at least two other modes: the fast wave¹¹ (whistler) and the ion Bernstein wave,¹² both of which can also be used to drive currents via electron Landau damping. Since the density limit of lower hybrid wave current drive is not well understood,¹⁰ it is not clear that they can be used in tokamak reactors. Therefore, it is important to consider other modes of plasma waves. In this paper, we present detailed ray tracing

calculations for the lower hybrid wave, fast wave, and ion Bernstein wave with reactor-like parameters and compare the merits of these modes in terms of wave accessibility and efficiency.

II. Ray Tracing Code

The ray tracing computer code¹³ follows the wave trajectories by numerically integrating the following equations:¹⁴

$$\frac{d\vec{r}}{dt} = - \frac{\partial D}{\partial \vec{k}} / \frac{\partial D}{\partial \omega} \quad , \quad (1)$$

$$\frac{d\vec{k}}{dt} = + \frac{\partial D}{\partial \vec{r}} / \frac{\partial D}{\partial \omega} \quad . \quad (2)$$

The conventional toroidal coordinates (r, θ, ϕ) are used with the assumption of concentric circular magnetic surfaces. ω and $\vec{k}$ denote the wave angular frequency and wave number which satisfy the local electromagnetic wave dispersion relation:¹⁵

$$D(\omega, \vec{k}) = \begin{vmatrix} K_{xx} - n_{\parallel}^2 & K_{xy} & n_{\perp} n_{\parallel} (1 + K_{xz}) \\ -K_{xy} & K_{xx} + K_{yy} - n_{\perp}^2 - n_{\parallel}^2 & n_{\perp} n_{\parallel} K_{yz} \\ n_{\perp} n_{\parallel} (1 + K_{xz}) & -n_{\perp} n_{\parallel} K_{yz} & K_{zz} - n_{\perp}^2 \end{vmatrix} = 0 \quad , \quad (3)$$

where $n \equiv kc/\omega$ and $\parallel, \perp$ denote components parallel and perpendicular to the magnetic field ($\vec{B} = B\hat{z}$), respectively. The K_{ij} are various elements of the hot plasma dielectric tensor¹⁵ with the finite-Larmor-radius terms included. For the parameters of our

interest, we can put $K_{xz} = 0$. The chosen plasma parameters are similar to those of the proposed FED device as shown in the following:

major radius:	$R_O = 458 \text{ cm}$	
minor radius:	$a = 120 \text{ cm}$	
toroidal magnetic field:	$B_O = 50 \text{ kG}$	
peak electron density:	$n_O = 2 \times 10^{14} \text{ cm}^{-3}$	
electron density profile:	$n(r) = n_O [0.01 + 0.99 \cos(\frac{\pi \cdot r}{2a})]$	
deuterium density:	$n_1(r) = n(r)/2$	
tritium density:	$n_2(r) = n(r)/2$	
safety factor:	$q(0) = 1.0$	$(r = 0)$
	$q(a) = 1.8 \text{ or } 3.8$	$(r = a)$
peak electron temperature:	$T_{eo} = 15 \text{ keV}$	
electron temperature profile:	$T_e(r) = T_{eo} [0.99 (1 - \frac{r^2}{a^2})^{2/3(q(a)-1)} + 0.01]$	
ion temperature:	$T_i(r) = T_e(r)$	
poloidal field profile:	$B_\theta(r) = \frac{B_O a^2 / (r q(a))}{R_O + r \cos \theta} \cdot [1 - (1 - \frac{r^2}{a^2})^{q(a)}]$	

In order to sustain a steady state tokamak with these parameters via electron Landau damping of plasma waves, good wave

penetration into the plasma core with $n_{\parallel} \sim 1.2 - 1.5$ is necessary.

III. Lower Hybrid Waves

In a cold plasma the lower hybrid wave dispersion relation is:

$$1 - \frac{\omega_{pi}^2}{\omega^2} - \frac{k_{\parallel}^2}{k^2} \frac{\omega_{pe}^2}{\omega^2} + \frac{k_{\perp}^2}{k^2} \frac{\omega_{pe}^2}{\omega_{ce}^2} = 0. \quad (4)$$

It is an electrostatic wave such that

$$\frac{E_{\parallel}}{E_{\perp}} = \frac{k_{\parallel}}{k_{\perp}}. \quad (5)$$

In slab geometry the wave can reach the lower hybrid resonance if it satisfies the accessibility condition:¹⁶

$$n_{\parallel}^2 > 1 + \frac{\omega_{pe}^2}{\omega_{ce}^2}, \quad (6)$$

which obviously favors low density and high magnetic field.

The situation can be quite different in the presence of a rotational transform. In a tokamak magnetic field, $n_{\parallel}$ varies along the wave trajectory¹⁷ and waves launched at the plasma edge may not reach the lower hybrid resonance even when they satisfy Eq. (6). This can be qualitatively illustrated as follows:

$$k_{\parallel} = k_{\theta} \cdot \frac{B_{\theta}}{B} + k_{\phi} \frac{B_{\phi}}{B}, \quad (7)$$

where the subscripts θ and ϕ denote the poloidal and toroidal directions, respectively.

Put $B_\phi = B_0 R_0 / (R_0 + r \cos \theta)$ and assume $1/q^2 \cdot r^2 / (R_0 + r \cos \theta)^2 \ll 1$, from Eq. (2), Eq. (4) and Eq. (7), one can easily show that

$$\frac{dk_{\parallel}}{dt} \approx - \frac{\omega}{q} \frac{\omega_{pe}^2}{\omega_{ce}^2} \frac{r \sin \theta}{(R_0 + r \cos \theta)^2} / (1 + \omega_{pe}^2 / \omega_{ce}^2) \quad (8)$$

Therefore, $n_{\parallel} = k_{\parallel} c / \omega$ varies along the wave trajectory. Ray tracing results in Fig. 1a show that $n_{\parallel}$ oscillates as one would expect from Eq. (8). The power deposition profile is shown in Fig. 1b for two values of $n_t = k_{\perp} c / \omega$ (1.2 and 1.5). There is only a minor difference between the two cases because wave absorption occurs mainly near the peak value of $n_{\parallel}$ along the wave trajectory (which is higher than the value of $n_{\parallel}$ launched at the plasma surface). Over 90% of the wave power is absorbed within the region $50 \text{ cm} < r < 90 \text{ cm}$ via electron Landau damping. Figure 1c and Fig. 1d show the ray trajectory projected on the poloidal and the toroidal planes. It is apparent that as the wave propagates into the plasma, the perpendicular wavelength gets shorter as the density increases, and the radial penetration is very slow. One may think intuitively that lower hybrid waves should be able to penetrate deeper into the plasma at higher frequencies because of the higher perpendicular group velocity. Ray tracing results show that this is not necessarily true in a tokamak magnetic field. Figure 2 shows the region of wave absorption for various wave frequencies. The optimum frequency for the chosen plasma parameters is about 1 GHz, and wave penetration becomes worse at

higher frequencies. This obviously contradicts our intuition. Wave penetration at higher frequencies is somewhat improved by raising $q(a)$. Careful examination of the wave parameters along its trajectory reveals that the radial group velocity v_{gr} is actually smaller for a higher wave frequency. In order to understand this behavior, let us put $R = R_0 + r \cos \theta$, $k_\theta = m/r$, $k_\phi = n/R$; from the cold plasma wave dispersion relation, we can obtain¹⁷

$$\frac{dk_\theta}{dt} = \frac{1}{r} \frac{\partial D}{\partial \theta} / \frac{\partial D}{\partial \omega} = - \frac{\omega \sin \theta}{R}$$

$$\frac{\omega_{pe}^2 / \omega_{ce}^2 + [1 + \omega_{pe}^2 / \omega_{ce}^2 - \omega_{pi}^2 / \omega^2] / (1 + m/nq)}{1 + \omega_{pe}^2 / \omega_{ce}^2} \quad (9)$$

It is apparent from Eq. (9) that k_θ can get large at high frequencies. Since

$$k_\perp = (k^2 - k_n^2)^{1/2} \approx (k_\theta^2 + k_r^2)^{1/2} \approx k_n \omega_{pe} / \omega = n_n \omega_{pe} / c \quad (10)$$

$k_\perp$ is almost independent of ω at a fixed value of n_n and a larger k_θ would yield a smaller k_r which can result in a lower group velocity in the radial direction. Ray tracing results indicate that raising the lower hybrid wave frequency from 1.15 GHz to 2 GHz reduces the radial group velocity by a factor

of ten. The wave at 2 GHz mainly propagates along the poloidal direction and damped near the plasma surface due to the slow radial penetration.

At very high wave frequencies (≥ 5 GHz), we find that instead of surface absorption, the wave is reflected near the plasma edge without damping. This happens because k_θ gets so large that it forces k_r to zero as shown in Fig. 3a. This would cause a reflection in the radial direction. When the reflected wave reaches the plasma edge, part of it will tunnel out of the plasma and interact with the vacuum chamber wall while the rest of it will be reflected back towards the plasma interior. One can follow the rays after many reflections, but one cannot control $n_{\parallel}$, especially for the waves reflected from the wall. The wave will be absorbed when $n_{\parallel}$ becomes large.

All the results presented up to now were obtained with initial k_θ set equal to zero. One can launch the wave with an appropriate k_θ so that k_r never goes to zero and the reflection can be avoided as shown in Fig. 3b and Fig. 3c. Another way to avoid reflection is to raise the magnetic field (Fig. 4). Yet neither of these methods can make the wave penetrate to the plasma center. From these results we can see that it is marginal to rely on lower hybrid waves to sustain a steady state tokamak reactor unless one can change the plasma parameters for better wave penetration, namely, lower the temperature and density and raise the magnetic field. It should be pointed out here that the wave power deposition profiles presented thus far were

obtained by assuming linear electron Landau damping due to a locally Maxwellian distribution function. In order to drive currents, quasi-linear effects should take place which flatten the slope of the distribution function, lower the damping rate, and improve the wave penetration.¹⁸

IV. Fast Waves

In a cold magnetized plasma, the fast wave dispersion relation can be expressed in a simple form:¹⁹

$$\omega \approx \frac{k^2 c^2}{2 \omega_{pe}} \omega_{ce} |\cos \alpha|, \quad (11)$$

provided that $\omega_{ci}/\cos \alpha \ll \omega \ll \omega_{LH}^2 \cos \alpha / \omega_{ci}$ where α is the angle between $\vec{k}$ and $\vec{B}$, i.e., $k_{||} = k \cos \alpha$, $k_{\perp} = k \sin \alpha$. In a slab geometry where $k_{\perp} = k_x$, $\vec{B} = B \hat{z}$, the group velocity of the wave is:

$$\vec{v}_g = \frac{\partial \omega}{\partial \vec{k}} = \frac{\omega}{k} \left[\sin \alpha, 0, \frac{1 + \cos^2 \alpha}{\cos \alpha} \right], \quad (12)$$

and the wave polarization is:

$$\vec{E} = E_x \left[1, i |\cos \alpha|, \frac{\omega}{\omega_{ce}} \sin \alpha \frac{|\cos \alpha|}{\cos \alpha} \right]. \quad (13)$$

The wave energy density is:

$$W_0 = \frac{1}{8\pi} |E_x|^2 n_{\perp}^2. \quad (14)$$

Fast waves with $n_{\perp} \sim 0(1)$ are mainly damped by electron Landau damping. Wave damping via transit time magnetic pumping is

negligible. In order to compare the effectiveness of current drive with fast waves vs lower hybrid waves, let us start with the one-dimensional quasi-linear diffusion equation:

$$\frac{\partial f}{\partial t} + \frac{e}{m} E \frac{\partial f}{\partial v} = \frac{\partial}{\partial v} \left(D \frac{\partial f}{\partial v} \right) + \left. \frac{\partial f}{\partial t} \right|_c, \quad (15)$$

where E = static electric field parallel to $\vec{B}$

$$D \approx \pi (e/m)^2 k_{\parallel} / \omega \frac{E_{\parallel}^2}{\Delta k_{\parallel}}$$

$E_{\parallel}$ = component of rf electric field parallel to $\vec{B}$

$\Delta k_{\parallel}$ = width of rf power spectrum

$\left. \frac{\partial f}{\partial t} \right|_c$ = collision term whose form depends on the collision model.

The steady state solution without static electric field is:

$$\frac{\partial f}{\partial v} = - \frac{1}{D} \int_v \left. \frac{\partial f}{\partial t} \right|_c dv. \quad (16)$$

Therefore, the slope of the electron distribution function is proportional to $1/D \propto 1/E_{\parallel}^2$ and one has a perfect plateau if $D \rightarrow \infty$. The effectiveness of a current driver via electron Landau damping can be characterized by the factor $\epsilon \equiv D/$ (wave power flux). A wave with a small value of ϵ will have weak electron Landau damping so that a large power flux is needed for a given value of D . If Landau damping is the only dissipation mechanism and the wave power spectrum remains unchanged inside the plasma, then the ratio of current density to power dissipation (J/P_{α}) is independent of ϵ ; but usually there are other competing dissipation mechanisms and a small ϵ may become undesirable. The value of ϵ depends on the wave

polarization and the group velocity which can be calculated from the dispersion relation. From Eq. (4) and Eq. (11) we can show that for reactor parameters,

$$\frac{\epsilon \text{ (Fast Wave)}}{\epsilon \text{ (Lower Hybrid Wave)}} = \frac{\omega_{pe}^2}{\omega_{ce}^2} \frac{1}{n_{\parallel}^2} \frac{\sin^2 \alpha}{1 + \cos^2 \alpha} \sim 0.1-1. \quad (17)$$

This means that fast waves can be almost as effective as lower hybrid waves for current drive in tokamak reactors.

Detailed ray tracing has been carried out in a toroidal geometry with the same set of plasma parameters as is listed in Section II. Due to the rotational transform, $n_{\parallel}$ varies along the wave trajectory as shown in Fig. 5a. Since the fast wave, by definition, has a longer perpendicular wave length compared with the slow wave, the wave penetrates faster into the plasma interior as shown in Fig. 5b and Fig. 5c, but the power deposition profile in Fig. 5d is quite similar to the lower hybrid wave case (see Fig. 2d). Figure 6 shows the wave absorption region at various frequencies. The optimum frequency is about 1 GHz and penetration at higher frequencies improves with higher q values. The similarity between the fast wave and the slow wave is not so surprising if one realizes that they can convert to each other and the wave characteristics should be similar near the mode conversion region. Figure 7a shows the familiar $k_{\perp}$ vs r curves for the illustration of mode conversion in a slab model. In a tokamak magnetic field, the situation is complicated by the rotational transform and the toroidal effect. Figure 7b shows $k_{\perp}$ vs r obtained from ray tracing calculations. One can see that lower hybrid waves

and fast waves almost coalesce at $r \sim 60$ cm where 99% of the wave energy has been dissipated.

Despite the similarities in the optimum wave absorption profile, the fast wave behaves quite differently from the lower hybrid wave in some other respects. When the fast wave is launched with initial $k_\theta = 0$ at the plasma edge, k_θ remains small ($k_\theta \ll k_r$), unlike lower hybrid waves, until the wave approaches the center of the plasma. When the wave is near the plasma center, k_θ can be large and this results in a reflection in the radial direction. Another important difference between the fast wave and the lower hybrid wave is the excellent penetration of fast waves at low frequencies ($f < 1$ GHz, see Fig. 6). At $f \sim 600$ MHz the wave can reach the plasma center, undergo a reflection, and propagate outward with very little damping. Stronger damping would occur at a higher plasma temperature. Therefore, if one wants to operate a steady state tokamak at a peak temperature of ~ 25 keV, fast wave current drive at this frequency range may be a viable option.

V Ion Bernstein Waves

The ion Bernstein wave¹² is a hot plasma wave which exists because of the finite ion Larmor radius effect. At low densities where $\omega_{pe}^2/\omega^2 \ll n_i^2$, the wave is electrostatic and the dispersion relation in a slab geometry is:

$$n_i^2 K_{xx} + n_e^2 K_{zz} = 0. \quad (18)$$

At high densities the wave becomes quasi-electrostatic, in that the energy density stored in the wave magnetic field becomes comparable to or even larger than in the wave

electric field, and one must use Eq. (3) for an accurate description of the wave dispersion relation. Unlike lower hybrid waves, ion Bernstein waves with a wide range of $n_{\parallel}$ have been shown previously to penetrate very easily into a hot-dense plasma.¹³ One can calculate the efficiency factor for ion Bernstein wave and obtain

$$\frac{\epsilon(\text{IBW})}{\epsilon(\text{LHW})} \approx 10^{-5} (k_{\perp} \rho_i)^7. \quad (19)$$

The $k_{\perp} \rho_i$ term was included to account for the resonance effect where $k_{\perp} \rho_i \rightarrow \infty$. Ion Bernstein wave is launched from the low field edge of the plasma where $k_{\perp} \rho_i \lesssim 1$ and propagated toward the ion cyclotron harmonic resonance. Therefore, the efficiency factor (or damping) which is negligible can increase rapidly near the resonance and reach $\mathcal{O}(1)$ for $k_{\perp} \rho_i \gtrsim 6$. This effect causes the wave which is initially undamped to damp strongly via electron Landau damping near the resonance layer which can be placed near the center of the plasma. In a reactor like high temperature situation ($T_e > 10$ keV), the damping is usually dominated by electron Landau damping rather than the ion cyclotron harmonic damping. As can be seen from Fig. 8a, the strong wave damping near the plasma center is due to this enhanced electron Landau damping near the second harmonic cyclotron resonance of the tritium ions. If there is no cyclotron harmonic layer inside the plasma, the wave can shine through with very little absorption. A somewhat surprising result

from ray tracing in a tokamak magnetic field is that $n_{\parallel}$ changes sign along the wave trajectory as shown in Fig. 8b. This would generate current in both directions and greatly reduce its effectiveness. Figure 9 shows the real and the imaginary part of the wave number $k_{\perp}$. One can see that $\text{Im}k_{\perp}$ becomes large when the ion Bernstein wave approaches the second cyclotron harmonic layer of the tritium ions (located at $r = 0$). The gap between the spikes is the region in which $n_{\parallel}$ goes through zero and changes sign because Landau damping cannot occur when $|n_{\parallel}| < 1$. Ion Bernstein waves, therefore, can be used to sustain a steady state tokamak only if we start out with an asymmetric electron distribution function so that only waves propagating in the preferred direction are damped and drive current. There is no need to launch unidirectional waves in such a current drive scheme.

VI. Summary and Discussion

We have analyzed the wave trajectories of the lower hybrid wave, fast wave, and ion Bernstein wave for steady state reactor parameters. The results are quite different from slab model calculations because of the rotational transform and the toroidal effects. It is found that each of the three modes has its own problems even under ideal situations. The lower hybrid wave is the most effective mode to plateau the electron distribution function, but it has difficulty reaching the

plasma center. Fast waves have good penetration only at low frequencies, which results in weak damping unless the electron temperature is very high. Ion Bernstein waves can penetrate very well, particularly for low $n_{\parallel}$. The difficulty lies in the fact that, for the ion Bernstein wave, $n_{\parallel}$ changes sign along its trajectory.

In this paper, we calculate the linear propagation and damping of waves in a 50% deuterium and tritium plasma. Non-linear effects, plasma density fluctuations, α -particle, and other impurity effects are not included. Since we confine ourselves to waveguide-launched waves, other low frequency modes like Alfvén waves²⁰ are not considered. It is interesting to note that Alfvén waves can be driven unstable by α -particles.²¹ One may be able to launch an unidirectional Alfvén wave, from an external source, and let the plasma amplify the wave and sustain the current. In this way most of the current drive power would come directly from the α -particles. This scheme substantially reduces the circulating power in the reactor, making it really attractive. This possibility will be a topic for future studies.

Acknowledgments

The authors would like to thank Dr. W. Hooke, Dr. D. Ignat, Dr. F. Perkins, Dr. T. H. Stix and Dr. E. Valeo for helpful discussions. This work was supported by the U.S. Department of Energy Contract No. DE-AC02-76-CH03073.

REFERENCES

- ¹N. J. Fisch, Phys. Rev. Lett. 41, 873 (1978).
- ²K. L. Wong, Phys. Rev. Lett. 43, 438 (1979).
- ³R. McWilliams, E. J. Valeo, R. W. Motley, W. M. Hooke, and L. Olsen, Phys. Rev. Lett. 44, 245 (1980).
- ⁴K. L. Wong, R. Horton and M. Ono, Phys. Rev. Lett. 45, 117 (1980).
- ⁵T. Yamamoto, T. Imai, M. Shimada, N. Suzuki, M. Maeno, S. Konoshima, T. Fujii, K. Uehara, T. Nagashima, A. Funahashi and N. Fujisawa, Phys. Rev. Lett. 45, 716 (1980).
- ⁶M. Nakamura, T. Cho, S. Kubo, T. Shimozuma, H. Kawai, K. Yamazaki, T. Maekawa, Y. Terumichi, Y. Hamada, and S. Tanaka, Phys. Rev. Lett. 47, 1902 (1981).
- ⁷S. C. Luckhardt, M. Porkolab, S. F. Knowlton, K.-T. Chen, A. S. Fisher, F. S. McDermott, and M. Mayberry, Phys. Rev. Lett. 48, 152 (1982).
- ⁸K. Ohkubo, S. Takamura, K. Kawahata, T. Tetsuka, K. Matsuura, N. Noda, K. Sakurai, S. Tanahashi, and J. Fujita, Nucl. Fusion 22, 203 (1982).
- ⁹M. Porkolab, J. J. Schuss et al., Proceedings of the International Conference on Plasma Physics and Nuclear Fusion Research (Baltimore, September 1982), paper IAEA-CN-41/C-4.

- ¹⁰S. Bernabei, C. Daughney, P. Efthimion, W. Hooke, J. Hosea, F. Jobes, A. Martin, E. Mazzucato, E. Meservey, R. Motley, J. Stevens, S. Von Goeller, and R. Wilson, Phys. Rev. Lett 49, 1255 (1982).
- ¹¹D. W. Ignat, Proceedings of the 4th Topical Conference on Radio-Frequency Plasma Heating (February 1981). The University of Texas, Austin, Texas, paper C-12.
- ¹²M. Ono and K. L. Wong, Phys. Rev. Lett. 45, 1105 (1980).
- ¹³M. Ono, T. H. Stix, K. L. Wong, and R. Horton, in Proceedings of the 2nd Joint Grenoble-Varenna International Symposium of Heating in Toroidal Plasmas (Commission of the European Communities. Directorate-General XII-Fusion Programme. Brussels, 1980) Vol. I, p 593.
- ¹⁴T. H. Stix, Theory of Plasma Waves (McGraw-Hill, New York, 1962) p. 58.
- ¹⁵J. E. Sharer, J. B. Beyer, D. T. Blackfield, and T. K. Mau, Nucl. Fusion 19, 1171 (1979).
- ¹⁶V. E. Golant, Soviet Physics—Tech. Phys. 16, 1980 (1972).
- ¹⁷D. W. Ignat, Phys. Fluids 24, 1110 (1981).
- ¹⁸F. J. Paoloni, R. W. Motley, W. M. Hooke, and S. Bernabei, Phys. Rev. Lett. 39, 1081 (1977).
- ¹⁹A. Bers, C. F. F. Karney, and K. Thilhaber, RLE Progress Report (Massachusetts Institute of Technology) No. 115, p. 186 (January 1975).

- ²⁰R. A. Demirkhanov, A. G. Kirov, L. F. Ruchko, and A. V. Sukachev, JETP Lett. 33, 28 (1981).
- ²¹M. N. Rosenbluth and P. H. Rutherford, Phys. Rev. Lett. 34, 1428 (1975); also K. T. Tsang, D. J. Sigmar and J. C. Whitson, Phys. Fluids 24, 1508 (1981).

FIGURE CAPTIONS

- Fig. 1. Characteristics of lower hybrid waves in a tokamak. (a) Variation of the parallel index of reflection along the wave trajectory. (b) Wave absorption profile at two initial values of n_t . (c) Wave trajectory projected on a poloidal plane. (d) Wave trajectory projected on a toroidal plane.
- Fig. 2. Locations of the wave absorption region for lower hybrid waves at various frequencies. P denotes the fraction of power remained in the wave when reflection takes place. (a) $q(a) \approx 1.8$, (b) $q(a) = 3.8$.
- Fig. 3. Reflection of high frequency (5 GHz) lower hybrid waves near the plasma edge, (a) k_r is forced to zero when k_θ increases, the wave is launched with $k_{\theta 0} = 0$. (b) When the wave is launched with $k_{\theta 0} = 0.42 \text{ cm}^{-1}$, k_r never goes to zero and reflection does not occur. (c) Wave absorption profile for $k_{\theta 0} = 0.42 \text{ cm}^{-1}$.
- Fig. 4. 5 GHz lower hybrid waves at a higher magnetic field ($B_0 = 75 \text{ kG}$). (a) k_r never goes to zero so that reflection does not occur. (b) Wave absorption profile.
- Fig. 5. Characteristics of fast waves in a tokamak (a) variation of the parallel index of reflection along the wave trajectory. (b) Wave absorption profile. (c) Wave

trajectory projected on a poloidal plane. (d) Wave trajectory projected on a toroidal plane.

Fig. 6. Location of wave absorption region for fast waves at various frequencies. P denotes the fraction of power remaining in the wave when reflection takes place. (a) $q(a) = 1.8$, (b) $q(a) = 3.8$.

Fig. 7. (a) Schematic of mode conversion between lower hybrid waves and fast waves in a slab geometry. (b) Variation of $k_{\perp}$ from ray tracing calculations of 1.15 GHz lower hybrid waves and fast waves.

Fig. 8. Characteristics of ion Bernstein waves ($f = 50.6$ MHz, $n_t = 1.4$, $q(a) = 1.8$). (a) Wave absorption profile, note that $f = 2 f_{CT}$ at $r = 0$. (b) variation of $n_{\perp}$ along the wave trajectory. (c) Wave trajectory projected on a poloidal plane. (d) Wave trajectory projected on a toroidal plane.

Fig. 9. Real and imaginary parts of the perpendicular wave number $k_{\perp}$ for ion Bernstein waves with the same parameters as those in Fig. 8.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9