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OF LOWER HYBRID AND ICRF WAVES

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July 1994

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Current drive by radio frequency waves is expected to play an important role in future tokamaks, e.g. TPX and ITER, where RF waves will be used to modify the current profile and/or drive central current in a plasma. The best results, so far, for RF current drive, in tokamaks with electron temperatures less than 10 keV, have been achieved using lower hybrid waves (LHW). It has been shown, experimentally and theoretically, that the LH current drive (CD) efficiency can be enhanced by using other RF waves, e.g. waves in the electron cyclotron and ion cyclotron range of frequencies (ICRF). This is accomplished primarily by pushing the electrons in the tail of the LH generated distribution function to higher momenta, where they become less collisional. In the case of ICRF waves, it has been found that mode-converted ion Bernstein waves (IBW) are more effective in pushing the electrons to higher momenta than the fast Alfvén waves (FAW) since the IBW diffusion coefficient is much larger than the FAW diffusion coefficient [1, 2]. This explains, for example, the enhanced LHCD efficiency observed in JET [3]. In LHCD JET experiments, with a minority ion resonance near the plasma center, FAW's were launched primarily for plasma heating, thereby resulting in a low engineering CD efficiency. However, there exist scenarios where direct ion heating is minimized and mode conversion to IBW's is maximized, and this can lead to a considerable improvement in the engineering CD efficiency. Numerical integration of a one-dimensional full wave code have recently shown [4] that in TFTR mode conversion from FAW to IBW can be significant and lead to electron heating, as suggested sometime ago [5, 6].

In this paper we discuss two crucial aspects of newly proposed scenarios for enhancing the current drive efficiency: the propagation and quasilinear deposition of IBW's, and maximizing the power mode converted to IBW's. We give an analytical form for the maximum mode-converted power which can form a basis for exploring optimized scenarios for the interaction of mode-converted IBW's with electrons.

Properties of the Diffusion Coefficient Along Rays

Assuming concentric circular flux surfaces, the flux-surface averaged, normalized, quasilinear diffusion coefficient for electrons is:

$$\langle D \rangle = \frac{1}{4\pi^2 r R_0 \alpha} \frac{D_0}{D_c} \frac{\delta t}{\delta r} P \tag{1}$$

where r is the radius of the flux surface, R_0 is the major radius, $D_c = m_e^2 v_{te}^2 \nu_e$ is the collisional diffusion, m_e is the electron mass, $v_{te} = \sqrt{T_e/m_e}$ is the electron thermal velocity, ν_e is the electron-electron collision frequency, δt is the time taken by a ray

to cross a flux surface of radial thickness δr, P is the power (in Watts) in the ray, $\alpha = (\epsilon_0 \omega/4)(\partial D_{ij}/\partial \omega)(E_i^* E_j/|E_y|^2)$, D_{ij} is the plasma dispersion tensor, and:

$$
D_0 = \frac{\pi e^2}{2\omega} \frac{c}{|v_\parallel|} \left[\left\{ \mathrm{Im}\left(\frac{E_z}{E_y}\right) J_0\left(\frac{k_\perp v_\perp}{\omega_c e}\right) + \frac{v_\perp}{v_\parallel} J_1\left(\frac{k_\perp v_\perp}{\omega_c e}\right) \right\}^2 \right.
$$
$$
\left. + \left\{ \mathrm{Re}\left(\frac{E_z}{E_y}\right) J_0\left(\frac{k_\perp v_\perp}{\omega_{ce}}\right) \right\}^2 \right] \delta\left(n_\parallel - \frac{c}{v_\parallel}\right) \tag{2}
$$

ω is the wave frequency, $k_\parallel$, $k_\perp$ are the wave vectors along and perpendicular to the total magnetic field, respectively, $n_\parallel = ck_\parallel/\omega$, c is the speed of light, $v_\parallel$ and $v_\perp$ are the parallel and perpendicular components of the electron velocity, respectively, $\vec{E}$ is the wave electric field, and ω_{ce} is the electron cyclotron frequency. The right hand side of (2) can be evaluated for a local solution of the plasma dispersion relation. The flux-surface averaged diffusion coefficient in (1) can then be determined along the appropriate ray trajectories.

In Fig. 1 we show the poloidal projection of a FAW ray launched after mode conversion. The parameters are: $R_0 = 3\,\mathrm{m}$, toroidal magnetic field on axis = $3.2\,\mathrm{T}$, plasma current = $1.5\,\mathrm{MA}$, peak electron density = 2×10^{19} m^{-3}, hydrogen minority (3% of the electron density) in a deuterium plasma, peak ion and electron temperatures = 5 keV, and the frequency of ICRF and LH waves is 48 MHz and 3.7 GHz, respectively. This ray propagates out to the edge where it gets reflected back into the plasma. Upon reaching the mode-conversion region the FAW ray mode converts to the IBW ray. The IBW ray stops when it is completely damped onto the electrons. The damping is enhanced due to a toroidal upshift of $|k_\parallel|$ as the IBW propagates away from the mode-conversion region [6]. Fig. 2 shows $\langle D \rangle$ per megawatt of power along this ray trajectory. The regions corresponding to FAW and to IBW are indicated on the figure. The increase in the IBW diffusion coefficient, and the comparison with the FAW diffusion coefficient, as the ray propagates away from the mode-conversion region is evident. For comparison, for one megawatt of power in a given ray, $\langle D \rangle \sim 10^2$ for LHW's; $\langle D \rangle \sim 10^{-2}$ for FAW's, and $\langle D \rangle \sim 1$ for IBW's.

In advanced tokamak scenarios where the plasma temperature is higher, the IBW's offer a distinct advantage provided there is an effective mode conversion from FAW's to IBW's. Unlike LHW's, which will damp near the edge of the plasma, FAW's and IBW's can propagate into the central part of the plasma. In addition, the LHW's have an accessibility limit at low $k_\parallel$'s which prevents their direct, phase-resonant interaction, with the fastest (and, hence, least collisional) electrons near c; the FAW's and IBW's do not have such a limit. However, in contrast to LHW's which damp strongly for $\omega/(k_\parallel v_{te}) \approx 3$, IBW's damp strongly for $\omega/(k_\parallel v_{te}) \approx 2$ while FAW's damp strongly for $\omega/(k_\parallel v_{te}) \approx 1$. Thus, the IBW's are interacting with a less collisional part of the electron distribution function than FAW's. In addition the diffusion coefficient for IBW's is much larger than for FAW's. The toroidal upshift in $|k_\parallel|$ of the IBW's depends on the plasma current and the toroidal magnetic field and is not sensitive to the plasma temperature. The upshift is large over short distances of propagation so that the IBW's interact strongly with the electron distribution in a region close to mode conversion.

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The approximate cold plasma dispersion relation for the FAW is:

$$n_\perp^2 = \frac{(L - n_\parallel^2)(R - n_\parallel^2)}{S - n_\parallel^2} \tag{3}$$

where $n_\perp = ck_\perp/\omega$, and S, R, and L are the usual Stix tensor elements. The dispersion relation gives two types of cutoffs for the FAW: the right-hand cutoffs (RHC) ($R = n_\parallel^2$), one of which is on the low-B_T side (LFS), usually near the plasma edge for good antenna coupling, and the other on the high-B_T side (HFS) that can be inside the plasma; and a left-hand cutoff ($L = n_\parallel^2$) which, in plasmas with two ion species, can be centrally located near the ion-ion hybrid resonance given approximately by $S = n_\parallel^2$. The propagation of the FAW through the resonance and cutoff(s) is given by:

$$\frac{d^2 E_y}{dx^2} + Q(x)\, E_y = 0 \tag{4}$$

where E_y is the normalized (poloidal) component of the electric field, x is the normalized spatial coordinate along the equatorial plane, and $Q(x)$ is the potential function [7], which for a cold plasma is equal to the right hand side of (3). In the absence of cyclotron absorption and in the case when the HFS-RHC is ignored, the potential function is approximated by the Budden potential: $Q(x) = \gamma - \beta/x = (x - x_L)/x$, where γ and β characterize the left-hand cutoff x_L. The scattering results are given by the well-known Budden coefficients. However, the Budden potential does not always adequately describe the propagation of the FAW since it ignores the HFS-RHC. The transmitted FAW can reflect back into the plasma from this cutoff. By increasing $k_\parallel$ and/or decreasing the density, the HFS cutoff moves in closer to the Budden resonance-cutoff pair forming a cutoff-resonance-cutoff triplet. The approximate, lossfree, potential function for this case is $Q(x) = x + \gamma - \beta/x = (x - x_L)(x - x_R)/x$ where x_R is the HFS-RHC. For this potential function (4) can be solved approximately for E_y. We find that the resultant power mode conversion coefficient is:

$$C = 1 - R, \quad \text{where} \quad R = (1 - T)^2 + T^2 + 2T(1 - T)\cos(\phi + 2\psi) \tag{5}$$

is the power reflection coefficient, $T = \exp(-\pi\eta)$ is the Budden transmission, $\eta = \beta/\sqrt{\gamma}$, ϕ is the phase difference between the transmitted FAW and the FAW reflected at the HFS cutoff, and ψ is the (coupling) phase of $\Gamma(-i\eta/2)$ where Γ is the Gamma function. By choosing these phases such that $\phi + 2\psi = m\pi$ (m being any odd integer) we find that $R_{min} = (1 - 2T)^2$ and $C_{max} = 4T(1 - T)$. Thus, for $T = 1/2$, $R_{min} = 0$ and $C_{max} = 1$, i.e. for these conditions the FAW is completely mode converted to IBW's. The phases ϕ and ψ depend on the (HFC) right-hand and left-hand cutoffs which, in turn, depend on the plasma parameters and $k_\parallel$. Thus, by modifying these parameters, the location of the RHC can be changed in order to maximize the mode conversion coefficient. For example, the HFS-RHC can move into the plasma as $k_\parallel$ is increased and/or the density is decreased; the LFS-RHC must be kept near

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the plasma edge for good antenna coupling. We find that for different tokamak scenarios, using realistic potentials for $Q(x)$ that account for finite Larmor radius effects and plasma profiles [7], mode-conversion coefficients very close to unity can be obtained. Figure 3 gives some numerical examples.

A simple physical picture of such strong (almost complete) absorption emerges by regarding the triplet $Q(x)$ as a resonant system coupled to by the FAW incident from the LFS. Complete absorption results when the incident FAW is critically coupled to the resonator formed by the cutoff-resonance-cutoff plasma system; the HFS right-hand cutoff adjusts the resonator, while the spacing between the left-hand cutoff and the resonance adjusts the coupling. This picture is borne out by the calculations of $R(k_\parallel)$ which exhibit the expected resonance behavior.

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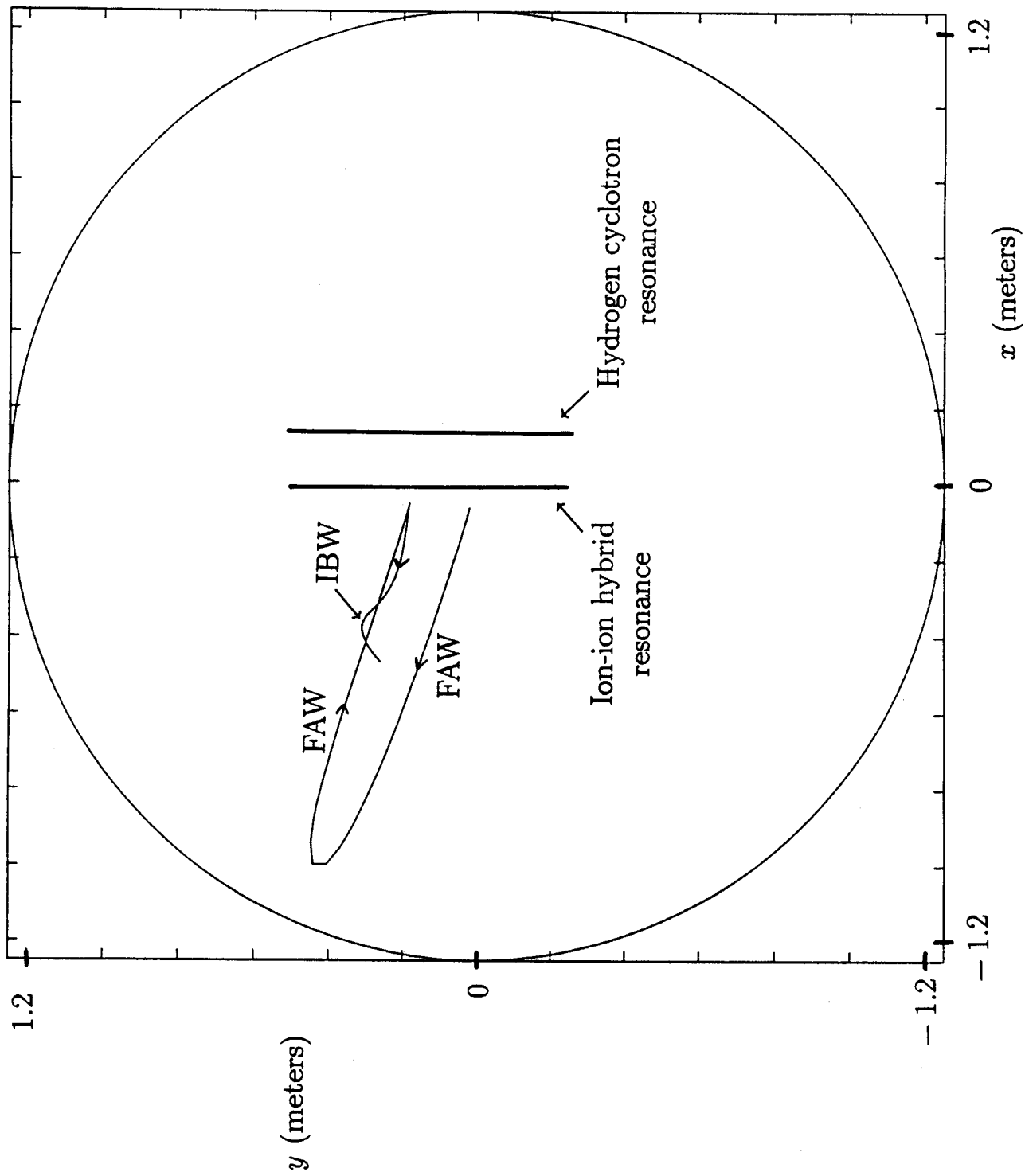
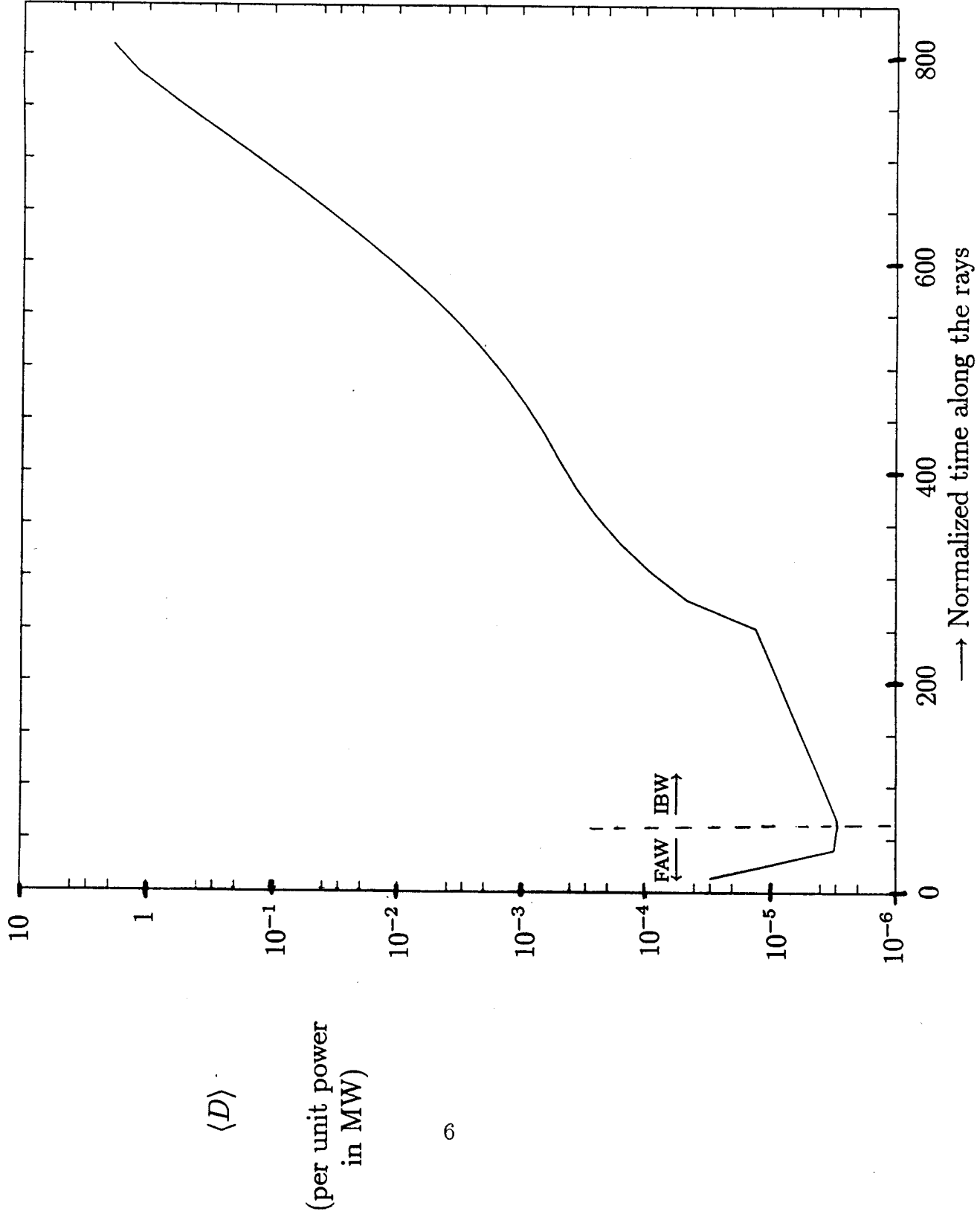Figure 1: Poloidal projection of FAW and IBW ray trajectories

Figure 2: Flux surface averaged, normalized, diffusion coefficient along the FAW and IBW.
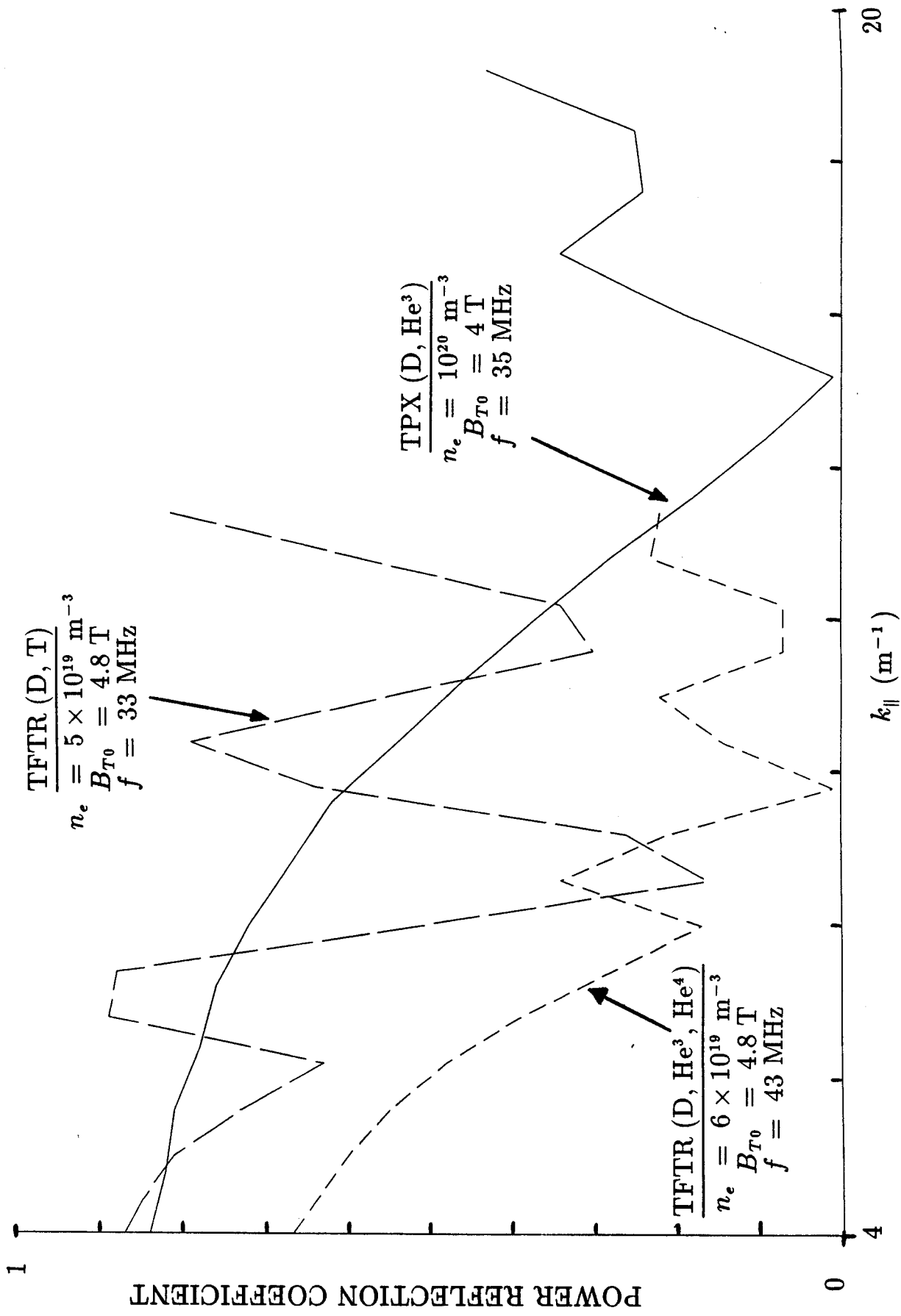
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$$\frac{\text{TPX (D, He}^3)}{\begin{aligned}n_e &= 10^{20}\ \text{m}^{-3}\\ B_{T0} &= 4\ \text{T}\\ f &= 35\ \text{MHz}\end{aligned}}$$

$$\frac{\text{TFTR (D, T)}}{\begin{aligned}n_e &= 5\times10^{19}\ \text{m}^{-3}\\ B_{T0} &= 4.8\ \text{T}\\ f &= 33\ \text{MHz}\end{aligned}}$$

$$\frac{\text{TFTR (D, He}^3,\ \text{He}^4)}{\begin{aligned}n_e &= 6\times10^{19}\ \text{m}^{-3}\\ B_{T0} &= 4.8\ \text{T}\\ f &= 43\ \text{MHz}\end{aligned}}$$

POWER REFLECTION COEFFICIENT

$k_{\parallel}$ (m^{-1})

FIGURE 3

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