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**ENHANCED CURRENT DRIVE  
WITH LOWER-HYBRID  
AND ION-BERNSTEIN WAVES**

**A. K. Ram, A. Bers, V. Fuchs and S. D. Schultz**

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## ENHANCED CURRENT DRIVE WITH LOWER-HYBRID AND ION-BERNSTEIN WAVES

### Abstract

The lower-hybrid current drive (LHCD) efficiency in ICRF heated plasmas is enhanced by mode converted ion-Bernstein waves (IBW) when the mode conversion region is in the central part of the plasma. This interaction could be responsible for the observed “synergy” in JET. An analytical model which parameterizes the conditions for enhanced mode conversion is derived and results for some tokamak scenarios are presented.

### 1. Introduction

Radio frequency (RF) waves are presently a significant means for heating plasmas and driving currents in tokamaks. RF waves are expected to play an important and significant role in future tokamaks, e.g. TPX and ITER. Combining the effects of two RF schemes with different frequencies, propagation, and interaction properties has proved beneficial in some experiments. It has been shown in JET that there is an enhancement in the LHCD efficiency in the presence of ICRF heating [1]. A similar effect was also observed in PBX-M when LHCD was used in the presence of IBW's [2]. We show that the LHCD efficiency in JET was likely enhanced by the interaction of the mode-converted IBW's with the suprathermal electrons generated by LHCD. The enhancement in the CD efficiency was limited since only a fraction of the input power (at most 20%) was mode converted. However, if the power mode converted can be enhanced then the interaction of IBW's with LHCD will become more efficient. We show that a fast Alfvén wave (FAW) cutoff on the high magnetic field side (HFS) of the ion-ion hybrid resonance (IHR) can effectively modify the mode-conversion coefficient so that, in principle, it is possible to mode convert all the incoming power.

### 2. Interaction of IBW'S with LHCD

In JET, the ICRF waves were launched with a symmetric  $k_{\parallel}$  spectrum so that there could be no net generation of current by the ICRF waves alone. It was observed that, in order to get an enhancement in the LHCD efficiency, the ICRF antennas had to be in a monopole configuration, so that most of the launched power was in the smaller  $k_{\parallel}$ 's, and that the ion-ion hybrid resonance had to be inside the plasma. The LHCD generated electron distribution function had an energetic, suprathermal electron population. One then expects

that LHCD efficiency would be enhanced if the symmetric ICRF wave spectrum could increase this asymmetry in the electron distribution function. Results from our extensive analytical and computational work [3-6] show that this is indeed the case. However, it is the mode-converted IBW's, not the FAW's, that lead to an effective increase in the CD efficiency. The computational results, using CQL3D [7,8], were obtained by solving the two-dimensional Fokker-Planck equation. We outline the main conclusions from our studies that have been reported elsewhere [3-6].

For JET-type parameters we find that the FAW diffusion coefficient is very small so that the FAW interacts weakly with the LHCD electron distribution function. However, the IBW diffusion coefficient, which is of the same order as the FAW diffusion coefficient at and near the mode conversion, increases rapidly with an increase in  $|k_{\parallel}|$  and  $|k_{\perp}|$  as the IBW's propagate away from the conversion region [9]. The IBW's, which are electromagnetic near mode conversion, acquire a large electrostatic component during their toroidal excursion so that the diffusion coefficient is dominated by the Landau contribution (as is the case for LHW's) instead of the transit-time magnetic pumping contribution (as is the case for FAW's). For parameters discussed in [6] we find that, for one megawatt of power in a given ray, the normalized diffusion coefficients for LHW's, IBW's, and FAW's are of the order of  $10^2$ , 1, and  $10^{-2}$ , respectively. Using the full quasilinear diffusion coefficients in CQL3D, we find that a symmetric spectrum of IBW's modifies the LHCD electron distribution function significantly enough to lead to an enhancement (factor of four for JET-type parameters) in the (physics) CD efficiency (Fig. 1), as observed in the experiments.

In advanced, high-temperature tokamaks, the penetration to the central plasma of FAW's and IBW's is much less restricted than for LHW's. The IBW's are strongly damped for  $\omega/(k_{\parallel}v_{te}) \approx 2$  while the FAW's are strongly damped for  $\omega/(k_{\parallel}v_{te}) \approx 1$  so that the IBW's are interacting with the less collisional part of the distribution function than the FAW's. In addition, the IBW diffusion coefficient is larger than the FAW diffusion coefficient, so that the IBW's could have a more effective interaction with LHCD (near the edge of the plasma) for modification of the current profile, or be effective in driving central plasma currents. Most importantly, the (engineering) CD efficiency of this interaction (which is low in JET as most of the FAW power went into ion heating) can be enhanced if most of the input ICRF power can be converted to IBW's.

### 3. Efficient Mode Conversion to IBW's

For efficient mode conversion of the ICRF-FAW power to IBW's the fundamental ion cyclotron layers should be near the edge or outside the

plasma, and the IHR layer should be in the central region of the plasma. In the simplest, one-dimensional (equatorial plane) description of the FAW, the local cold-plasma dispersion relation is:

$$n_{\perp}^2 = \frac{(L - n_{\parallel}^2)(R - n_{\parallel}^2)}{S - n_{\parallel}^2} \quad (1)$$

where  $n_{\perp} = ck_{\perp}/\omega$ ,  $n_{\parallel} = ck_{\parallel}/\omega$ , and  $S$ ,  $R$ ,  $L$  are the usual Stix tensor elements.  $R = n_{\parallel}^2$  gives the positions of the right-hand cutoffs (RHC). There are usually two such cutoffs: one on the low magnetic field side (LFS), usually near the antenna, and another on the HFS. The positions where  $L = n_{\parallel}^2$  and  $S = n_{\parallel}^2$  correspond to the left-hand cutoff (LHC) and IHR, respectively. Usually, the LHC and the IHR are close to each other and define the Budden-type cutoff-resonance pair. In the vicinity of this region, local analysis leading to (1) breaks down and the propagation of FAW's is described by a differential equation:

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

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 [10], which for a cold plasma is equal to the right-hand side of (1). For the Budden-type cutoff-resonance pair  $Q(x) = \gamma - \beta/x$  where  $\gamma$  is related to  $n_{\perp}^2$  of (1), and  $\beta$  characterizes the LHC. The usual Budden result for power transmission coefficient is  $T_B = \exp(-\pi\eta)$ , where  $\eta = \beta/\sqrt{\gamma}$  [11]. The power reflection and power mode-conversion coefficients are  $R_B = T_B(1 - 2T_B)$  and  $C_B = T_B(1 - T_B)$ , respectively. Thus, the maximum power mode conversion coefficient can be only 25%.

However, reflection of the FAW at the HFS-RHC can increase the mode conversion significantly if the placement of the HFS-RHC with respect to the IHR layer is well chosen. Let us assume that the FAW that transmits through the IHR-LHC pair does not undergo any damping and is completely reflected at the HFS-RHC. This introduces only a phase difference between the transmitted FAW incident on the HFS-RHC and its subsequent reflection at this point. Let this phase difference be  $\pi + \phi$ . The power reflection coefficient for the cutoff-resonance-cutoff triplet is then given by [6,12]:

$$R_t = T_B^2 + (1 - T_B)^2 - 2T_B(1 - T_B) \cos(\phi + 2\psi) \quad (3)$$

where  $\psi$  is the phase of  $\Gamma(-i\eta/2)$  and  $\Gamma$  is the Gamma function. If there is no damping of the FAW between the antenna and the IHR-LHC pair then  $1 - R_t = C_t$  gives the fraction of the total ICRF power that is mode

converted to IBW's and/or damped in the mode-conversion region. It is easy to see that  $C_t = 1$  for  $\phi + 2\psi = 0$  and  $T_B = 1/2$ . The physics leading to this is similar to the behavior of a transmission line coupled to a dissipative resonator: complete absorption results when the incident FAW is critically coupled to the resonator formed by the LHC-IHR-RHC plasma system; the HFS-RHC adjusts the resonator while the LHC-IHR adjusts the coupling. Figure 2 shows contours of constant reflection as a function of  $\phi$  and  $\eta$ .

#### 4. Applications to Present and Future Experiments

Figure 3 shows the mode-conversion coefficient for parameters relevant to recent TFTR experiments [13]. The theoretical curve is the result obtained from (3) with the phase  $\phi$  given by the integral of  $\sqrt{Q(x)}$  between the HFS-RHC and the IHR layer [12]. The numerical value is obtained by integrating (2) with the complete  $Q(x)$  including thermal effects. The effect of the total phase in (3) is evident in Fig. 3. The conversion efficiency can be as high as 90% if the antenna  $k_{\parallel}$  are in the appropriate range.

For given tokamak parameters one can find the range of  $k_{\parallel}$ 's and densities that would optimize the choice of  $\eta$ . Figure 4 shows, for TPX-type parameters, contours of constant  $\eta$  as a function of electron density and  $k_{\parallel}$ . The curves are labelled to indicate the minimum power reflection coefficient (3) for that particular  $\eta$ . High mode conversion at high densities in large (major radius) tokamaks require high  $k_{\parallel}$ 's that may entail significant ion damping. Compromise scenarios will have to be worked out by carefully evaluating this damping.

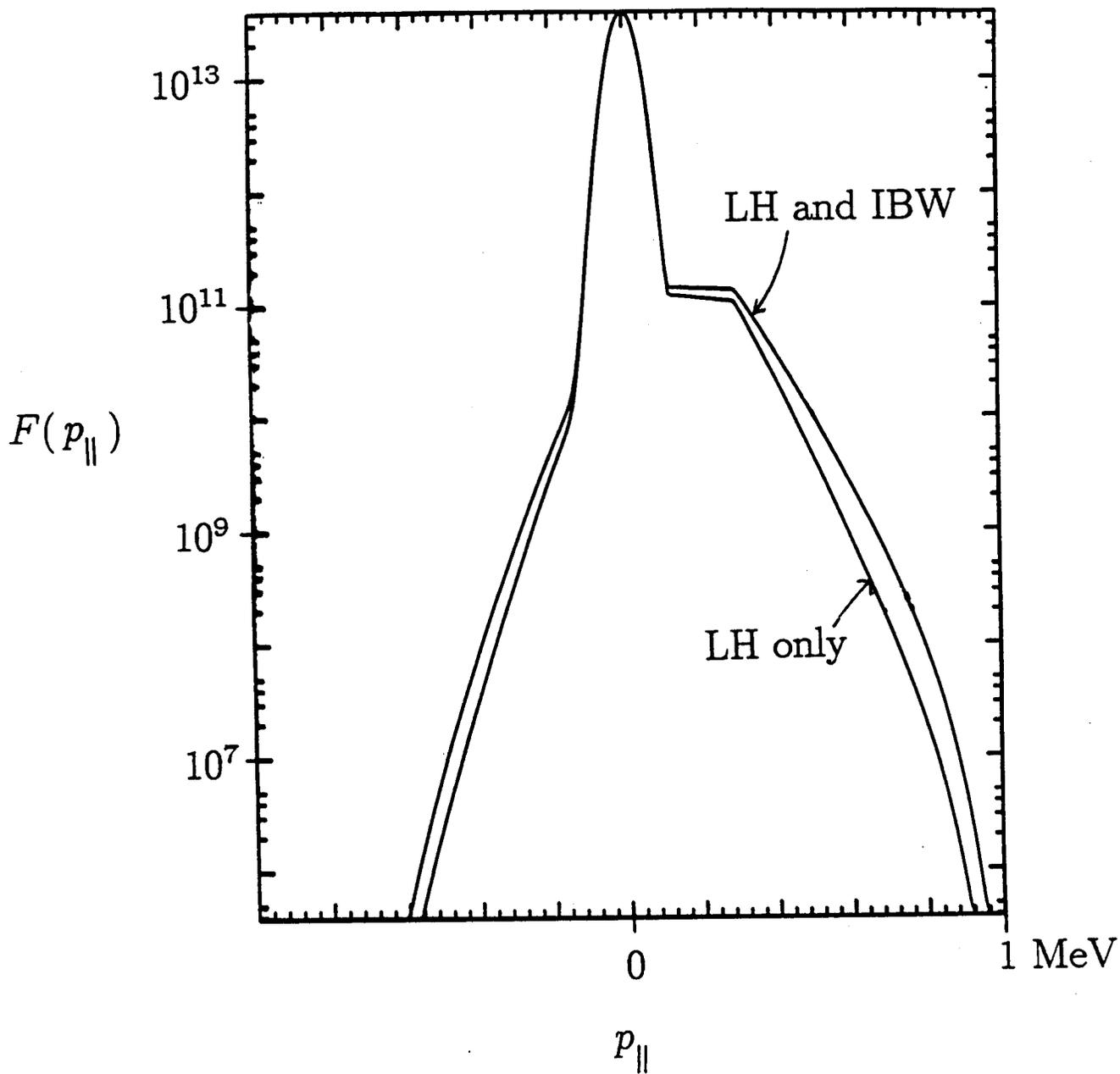
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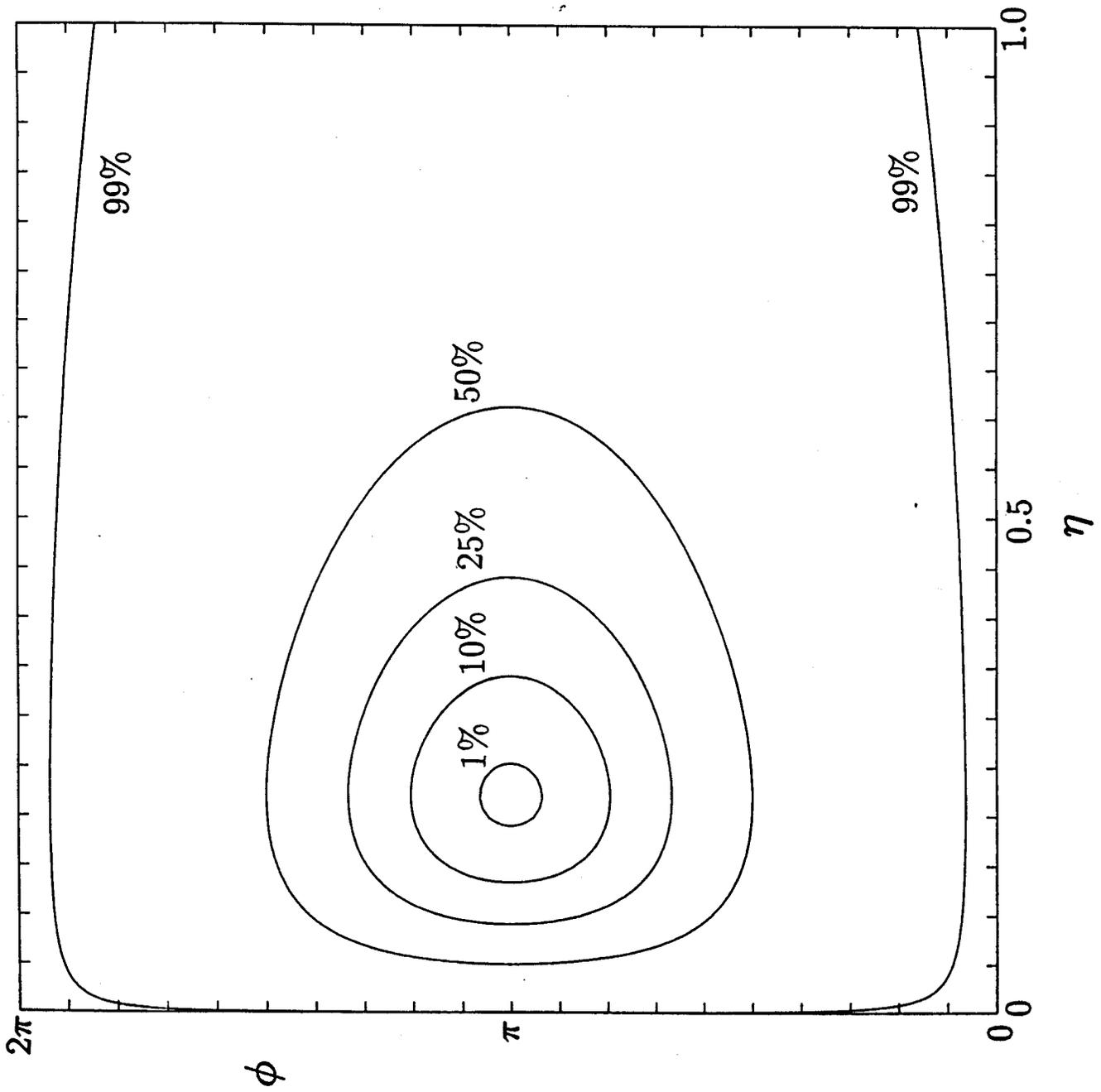
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## FIGURE CAPTIONS

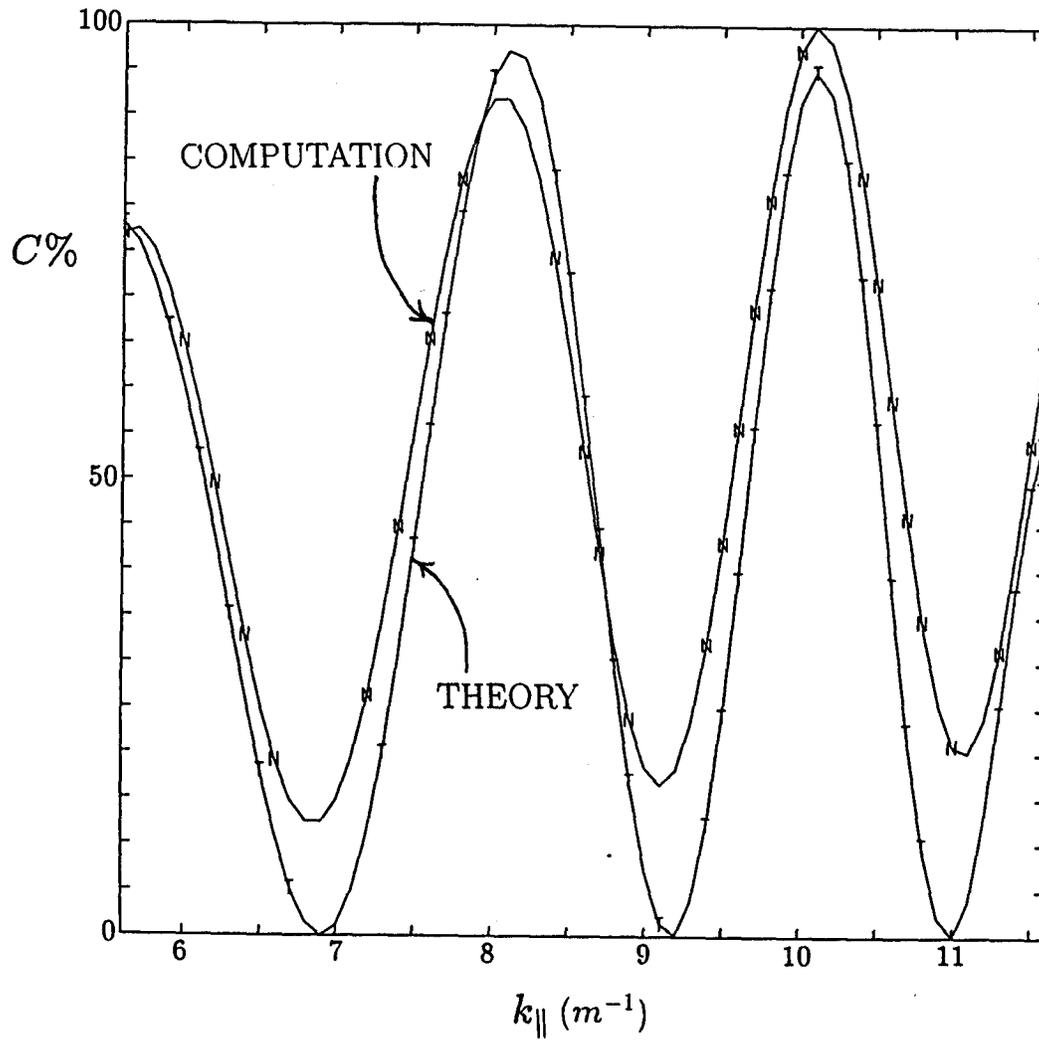
- Fig. 1 The parallel (to the magnetic field) electron distribution function (integrated over perpendicular momentum) for the case of LHW's only and for the combined case of LHW's and IBW's. The parameters are: electron density =  $2 \times 10^{19} \text{ m}^{-3}$ , magnetic field = 3.7 Tesla, plasma temperature = 4 keV, 3% hydrogen minority in deuterium plasma, LH frequency = 3.7 GHz, ICRF frequency = 48 MHz,  $\bar{D}_0^{LH} = 20$ ,  $\bar{D}_0^{IBW} = 10$  (see [4] for details).
- Fig. 2 Theoretical contours of percent power reflection in the  $(\phi, \eta)$  plane; the figure is  $2\pi$ -periodic in  $\phi$ . For large conversion (small reflections) the range of  $\eta$ 's is relatively narrow.
- Fig. 3 Mode-conversion power coefficient as a function of  $k_{\parallel}$  for TFTR-type experimental parameters:  $R_0 = 2.62 \text{ m}$ ,  $a = 0.95 \text{ m}$ ,  $(D, {}^3\text{He}, {}^4\text{He} / 0.31, 0.14, 0.2)$ ,  $B_0 = 4.8 \text{ Tesla}$ ,  $f = 43 \text{ MHz}$ ,  $n_{e0} = 3.5 \times 10^{19} \text{ m}^{-3}$  (parabolic profile),  $T_{e0} = 6 \text{ keV}$ , and  $T_{i0} = 7 \text{ keV}$  (parabolic-squared profile). The "theory" curve is from analytic results assuming no damping. The "computation" curve is from numerical integration of (2) in which  $Q(x)$  accounts approximately for electron and ion damping.
- Fig. 4 Contours of constant  $\eta$  giving the indicated minimum percent reflection in  $(n_e, k_{\parallel})$  space for TPX-type parameters:  $R_0 = 2.25 \text{ m}$ ,  $a = 0.5 \text{ m}$ ,  $(D, {}^3\text{He} / 0.5, 0.5)$ ,  $B_0 = 4 \text{ Tesla}$ ,  $f = 35 \text{ MHz}$ .



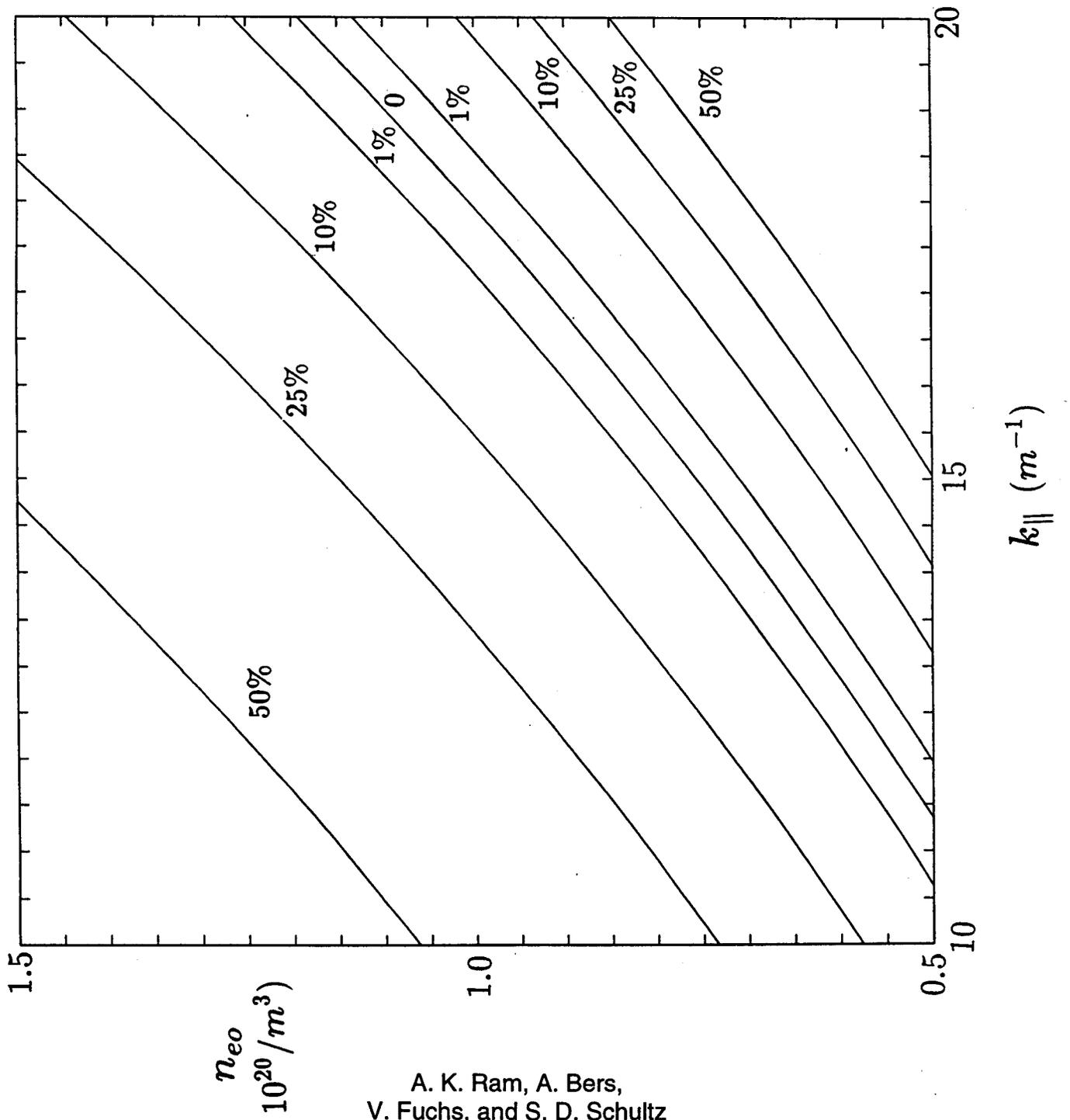
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Figure 1



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 Figure 2



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Figure 3



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 Figure 4