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EFFICIENT CURRENT DRIVE BY MODE-CONVERTED ION-BERNSTEIN WAVES

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Abstract. The rapid changes in $k_{\|}$, due to toroidal propagation, of mode-converted ion-Bernstein waves (IBW) can lead to a loss in the unidirectionality of the initial ICRF spectrum. This will lead to a reduction in the current drive efficiency. From numerical modelling of TFTR scenarios, we find that if, at mode conversion, $|k_{\|}| < k_c$ where $\omega/(k_c v_{te}) \approx 1.3$, ω is the ICRF frequency, and v_{te} is the electron thermal velocity near the mode conversion region, then the IBWs damp on electrons without loss of unidirectionality of the spectrum.

INTRODUCTION

In an ICRF-heated tokamak plasma, IBWs can be excited indirectly inside the plasma by mode conversion of the fast Alfvén waves (FAW) near the ion-ion hybrid resonance. The damping of IBWs near the mode-conversion region is an important property which can be used for possible modification of the plasma current profile, e.g., for the reversal of shear near the plasma edge for enhanced plasma confinement. In a previous study [1], we had shown that if FAWs with $k_{\|} \approx 0$ (where $k_{\|}$ is the component of the wave vector along the total magnetic field) undergo mode conversion, then it is difficult to generate plasma currents with the IBWs even though the IBWs interacted very efficiently with electrons. This was due to the fact that before the damping of IBWs, the $k_{\|}$'s tend to shift towards negative values above the equatorial plane and towards positive values below the equatorial plane in a tokamak. Thus, it was difficult to maintain the unidirectionality of the launched FAW spectrum needed for efficient current drive. However, we have recently shown that it is possible to efficiently mode convert FAWs having large values of $|k_{\|}|$ [2]. Also, experiments on TFTR have demonstrated current drive by mode-converted IBWs [3]. In light of these developments, we re-examine the propagation and damping of IBWs when large $|k_{\|}|$ can undergo mode conversion [4]. The basic question we try to answer is the following: what is the minimum $|k_{\|}|$ required at mode conversion so that the unidirectionality of the launched FAW spectrum is maintained as the IBWs propagate and subsequently damp on the electrons?

CONDITION FOR UNIDIRECTIONALITY

The results from our previous analysis [1] have been very useful in determining the general characteristics of the propagation and damping of IBWs in different plasmas, even though that analysis was for a plasma composed of deuterium ions with a small fraction of hydrogen ions. The geometric optics ray trajectory analysis shows that $|k_{||}|$ changes rapidly along the IBW rays and that IBWs damp via electron Landau damping, usually near the ion-ion hybrid resonance. The change in $k_{||}$ is given by:

$$\Delta k_{||} \approx -\frac{3\delta}{8}\sin(\theta)\frac{\omega_{cD}}{v_{tD}}\frac{B_\theta}{|B|}\frac{|\Delta r|}{R} \tag{1}$$

where θ is the poloidal angle ($\theta = 0$ corresponding to the equatorial plane on the low-field side), $\delta = \omega/(2\omega_{cD} - \omega)$, ω_{cD} is the deuterium cyclotron frequency, ω is the ICRF frequency, $v_{tD} = \sqrt{\kappa T_D/m_D}$ is the deuterium thermal velocity, B_θ is the poloidal magnetic field, B is the total magnetic field, R is the major radius of the tokamak, and Δr is the radial distance of propagation of the ray. From (1), we note that the sign of $\Delta k_{||}$ is negative in the upper half poloidal cross-section of the plasma and positive in the lower half poloidal cross-section. This is the primary effect that can cause the loss of directionality of a launched FAW spectrum.

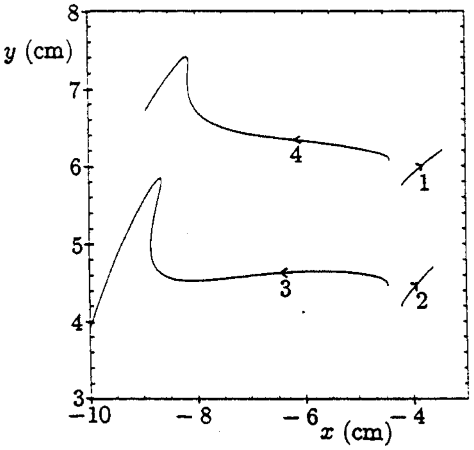
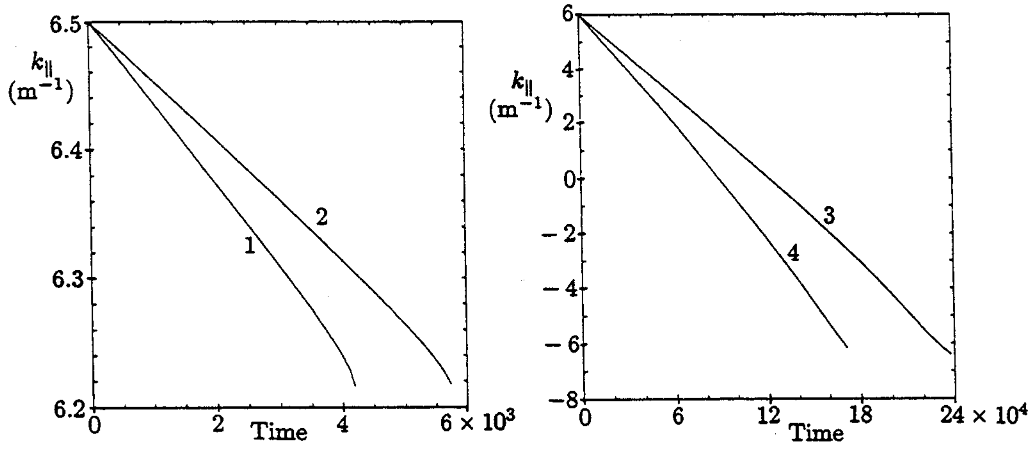


Figure 1: A magnified view of the poloidal projection of the IBW ray trajectories for TFTR-type parameters. The plasma is composed of D-^{3}He-^{4}He-C ions with the density ratios of $n_D : n_{^3He} : n_{^4He} : n_C = 0.12 : 0.25 : 0.1 : 0.03$. The peak electron density n_0 is 5.5×10^{19} m^{-3}, the peak electron and ion temperatures T_0 are 6.5 keV, the toroidal magnetic field on the axis is 4.8 T, the toroidal current is 1.4 MA, the density profile (normalized to the peak density) for the electrons and ions is $0.05 + 0.95(1 - \rho^2)$, and the temperature profile (normalized to T_0) is $0.05 + 0.95(1-\rho^2)^2$ where $\rho = r/a$ (r is the radial location and $a = 0.95$ m is the minor radius). The major radius is 2.62 m, f_{ICRF} =43 MHz, and the initial $k_{||}$'s of the rays are 6.5 m^{-1} (rays 1 and 2) and 6.0 m^{-1} (rays 3 and 4). The center of the plasma is at $x = y = 0$, the low-field side corresponds to $x > 0$, the equatorial plane is along $y = 0$, and the ion-ion hybrid resonance surface passes through $x \approx 0$.

Figure 1 shows a magnified view of the poloidal projection of four IBW rays, with different initial conditions, as they propagate away from the mode-conversion region in a TFTR-type plasma [3]. We note that the IBWs, which are allowed to propagate until they have damped, do not propagate very far from the ion-ion hybrid resonance (located near $x \approx 0$) before damping on electrons. Since these rays are launched in the upper half poloidal plane $y > 0$, their $\Delta k_{\|}$ should be negative during the propagation. Figures 2a and 2b show that indeed this is the case.



Figures 2a and 2b: The (normalized) time evolution of $k_{\|}$ along rays 1 and 2, and rays 3 and 4, respectively.

However, the rays which were launched with initial values of $k_{\|} = 6.5\ \mathrm{m}^{-1}$ (rays 1 and 2) do not change their sign of $k_{\|}$ before damping. The rays with initial $k_{\|} = 6\ \mathrm{m}^{-1}$ (rays 3 and 4) change their sign of $k_{\|}$ before damping. There are two important points to observe from this simulation. The first point is that if the initial magnitude of $k_{\|}$ at mode conversion is large enough, the IBWs propagate and damp on electrons without changing the sign of $k_{\|}$. The second point is that the damping of the IBWs on electrons is localized to being near the mode-conversion region regardless of the $k_{\|}$ spectrum. For rays 3 and 4 in Fig. 1, the $k_{\|}$ spectrum undergoes a complete reversal of sign over a short distance of propagation (Fig. 2b). From similar numerical simulations, we have found that the condition for maintaining a unidirectional spectrum after mode conversion is:

$$\frac{\omega}{|k_{\|c}|} \lesssim 1.3 v_{te} \qquad (2)$$

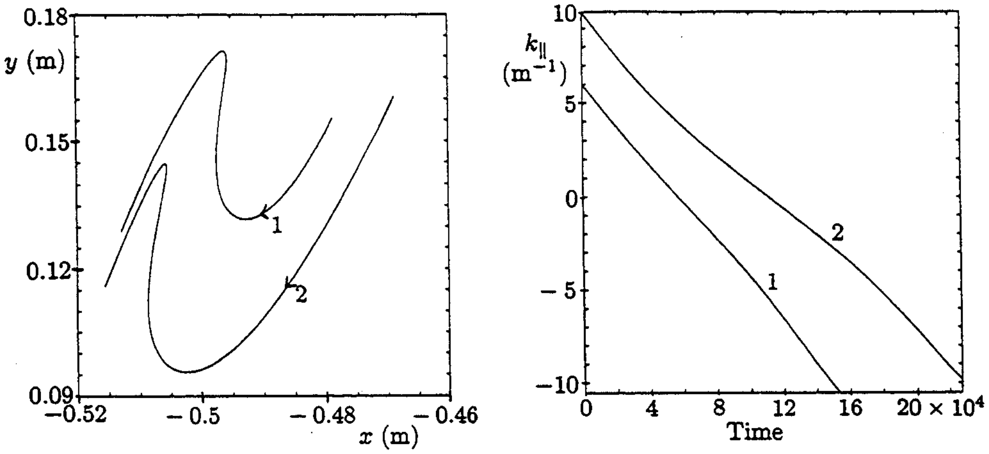
where ω is the ICRF frequency, $k_{\|c}$ is the value of $k_{\|}$ in the mode-conversion region, and v_{te} is the local electron thermal velocity where the IBW is launched. This result depends very crucially on the second point mentioned above.

OFF-AXIS DAMPING OF IBWs ON ELECTRONS

From [1], the radial distance of propagation of an IBW ray before it electron Landau damps is:

$$\Delta r\,|_{ELD} \sim \frac{8}{3\delta}\frac{\omega}{\omega_{cD}}\frac{|B|}{B_\theta}\frac{R}{\sin(\theta)}\frac{v_{tD}}{v_{te}}\,. \qquad (3)$$

An important feature of the IBWs emerges from this equation, namely that, if the ion and electron temperature profiles are the same, the radial distance of propagation depends essentially on the ratio of the ion to electron temperatures. Thus, IBW rays will propagate almost the same radial distance from the mode-conversion region before electron Landau damping whether the region is near the center of the plasma or near the edge of the plasma. In order to illustrative this, we consider the same TFTR-type parameters as in Fig. 1 except that f_{ICRF} =52 MHz. This places the mode-conversion region towards the inside edge of the plasma (near $x \approx -0.45m$) into the high magnetic field region. Figure 3a shows the magnified poloidal projection of two IBW rays with initial $k_{\|}$ of 6 m^{-1} (ray 1) and 9.9 m^{-1} (ray 2). As suggested by (3), the two rays damp near the ion-ion hybrid resonance even when the resonance is moved into the lower temperature part of the plasma. Figure 3b shows the corresponding changes in $k_{\|}$ as the IBWs propagate away from the mode-conversion region. The $k_{\|}$ changes sign for both rays. However, nearly 90% of the energy of ray 1 is damped on electrons before $k_{\|}$ changes sign. Thus, the initial $k_{\|}$ of ray 2 is close to the value for which the entire energy of the IBWs is deposited on electrons without changing the sign of $k_{\|}$. In accordance with (2), the initial $k_{\|}$ of the IBW has to be larger, compared to the case of Fig. 1 where the mode-conversion region was at higher temperatures, so that the IBWs can damp without a change in the sign of $k_{\|}$.



Figures 3a and 3b: A magnified poloidal projection of two rays and the (normalized) time evolution of $k_{\|}$ along these rays, respectively.

ACKNOWLEDGEMENTS

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