

EFFECT OF MODE TRANSFORMATION ON LOWER HYBRID CURRENT DRIVE

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1. Introduction

The lower hybrid (LH) wave is known to have two possible modes of propagation: the so-called slow mode and the fast mode. In LH current drive experiments, the wave is launched as a slow wave but during the propagation part of the power can transform to a fast wave. The transformation is known [1,2,3,4] to be possible for the slow wave that is accessible to the tokamak plasma centre and is launched with a toroidal refractive index spectrum extending below a certain threshold [3].

In comparison to the slow wave, the fast wave has different propagation and damping characteristics, its interaction with alpha particles and other fast ions is distinct, it has a small n_{\parallel} shift, etc. These properties and the transformation process itself are implicitly taken into account in most modern ray-tracing codes, and should therefore appear in the results. Typically, output of such codes contains power deposition and driven current calculated from a number of ray trajectories but does not reveal neither the occurrence of transformation nor its effect on the results.

In the present report, the characteristics and the occurrence of mode transformation and its effect on the power deposition in LH current drive are investigated. Rays launched in the slow mode are followed to find the possible transformation to the fast mode and to resolve the power deposited in each of these modes, respectively. In contrast to previous understanding, the fast wave is found to contribute significantly to the power deposition and to constitute even more than half of the absorption in an ITER-like configuration.

2. Transformation from the slow to the fast mode

To obtain a qualitative idea of the occurrence of mode transformations we first consider the cold plasma dispersion relation for lower hybrid waves. The perpendicular refractive index of an LH wave can be written as

$$n_{\perp}^2 = [A \pm \sqrt{A^2 - 4SB}]/2S, \quad (1)$$

where $A = (S + P)(S - n_{\parallel}^2) - D^2$ and $B = P[(S - n_{\parallel}^2)^2 - D^2]$ and S , P and D are elements of the dielectric tensor. Here, the plus sign corresponds to the slow mode and the minus sign to

the fast mode.

The lower hybrid wave can propagate only in a region where the expression $A^2 - 4SB$ under the square root is positive, which requirement gives the generalized Golant-Stix condition. A mode transformation happens whenever the ray approaches the point where this expression vanishes, i.e.,

$$[(S + P)(n_{\parallel}^2 - S) + D^2]^2 - 4SP[(S - n_{\parallel}^2)^2 - D^2] = 0. \quad (2)$$

Equation (2) defines n_{\parallel} surfaces in r - θ space.

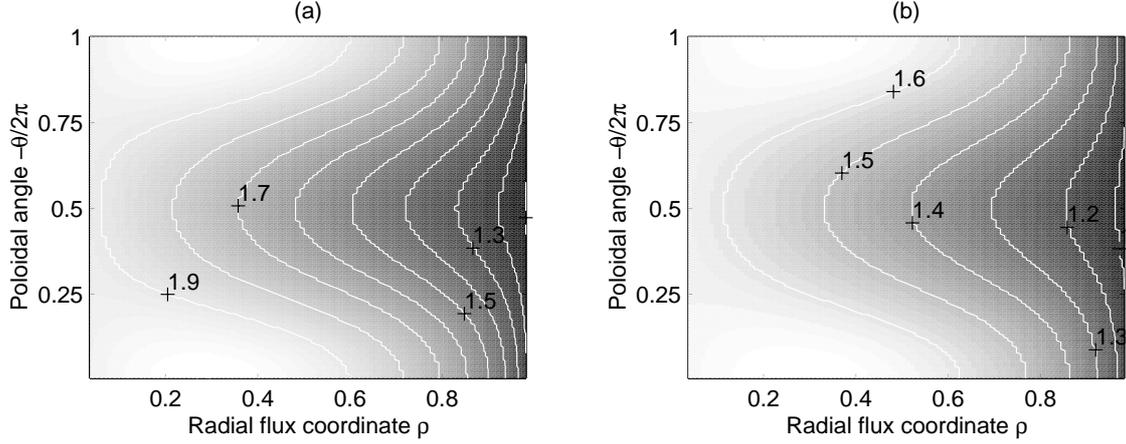


Figure 1. A contour plot of the values of n_{\parallel} on the mode transformation surface for an ITER-like tokamak. The central densities are: (a) $n_{e0} = 2.0 \times 10^{20} \text{ m}^{-3}$ and (b) $n_{e0} = 1.0 \times 10^{20} \text{ m}^{-3}$.

In the following, we consider an ITER-like tokamak with a major radius of $R_0 = 8.1 \text{ m}$ and a minor radius of $a = 2.8 \text{ m}$. We assume a magnetic field of $B_0 = 5.7 \text{ T}$ on the magnetic axis and a plasma current $I = 21 \text{ MA}$. The radial electron density profile is $n_e(r) = n_{e0}(1 - r^2/a^2)^\beta + n_{e1}$, where $n_{e1} = 10^{17} \text{ m}^{-3}$ and $\beta = 1$. The electron temperature profile was $T_e(r) = T_{e0}(1 - r^2/a^2)^\gamma + T_{e1}$, where $T_{e0} = 10 \text{ keV}$ and $T_{e1} = 100 \text{ eV}$ and $\gamma = 1.5$. The frequency of the LH waves is $f = 5 \text{ GHz}$ and the width of the toroidal refractive index spectrum (FWHM) is $\Delta n_{\phi 0} = 0.13$. The poloidal launching position of the rays is $-0.3 \text{ rad} \leq \theta_0 \leq 0.3 \text{ rad}$, and the initial poloidal mode number is $m_0 = 0$.

Let us first consider the mode transformation surface defined by the condition (2) in a tokamak with a circular cross section. The values of n_{\parallel} on the mode transformation surface are depicted in r - θ space in Fig. for two central densities. In order for the ray to reach this surface, its n_{\parallel} has to reduce. The mode transformation surface has a distinct minimum of n_{\parallel} in the region around $\theta = \pi$, i.e., on the high field side of the tokamak. Correspondingly, there is a maximum of the surface on the low field side at $\theta = 0$. On the low field side, a smaller down shift in n_{\parallel} is enough for obtaining a mode transformation. Therefore, one could expect that mode transformation occurs more often on the low field side than on the high field side.

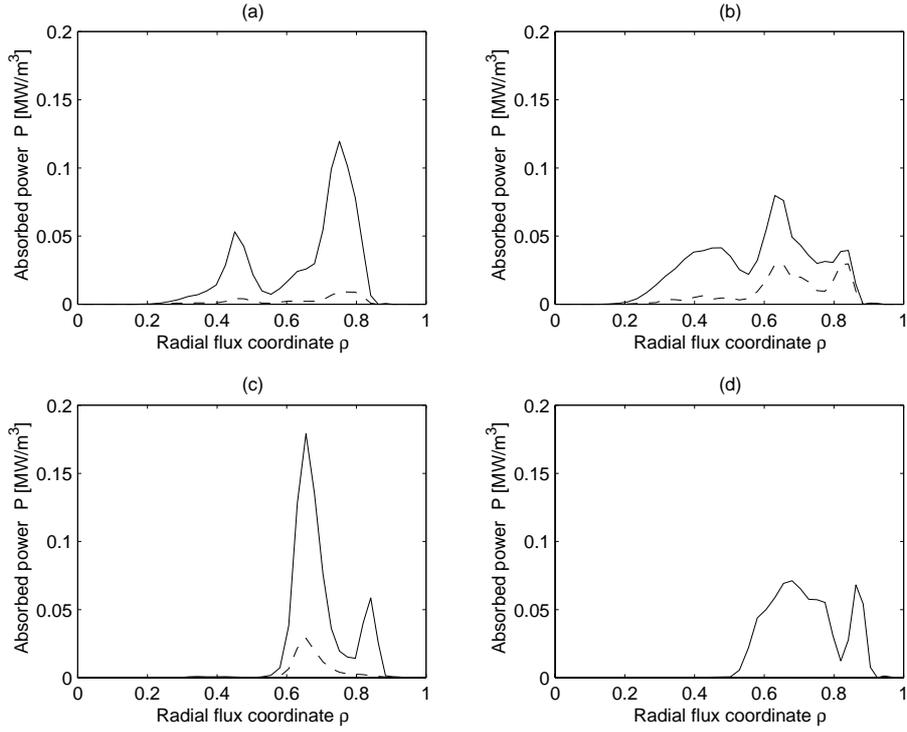


Figure 2. The total absorbed power density (solid line) and the power density absorbed as a fast wave (dashed line) in an ITER-like tokamak. The initial values of the toroidal refractive index are:

(a) $n_{\phi 0} = 1.6$, (b) 1.8 , (c) 2.0 , (d) 2.4 ($n_{e0} = 1.0 \times 10^{20} \text{ m}^{-3}$).

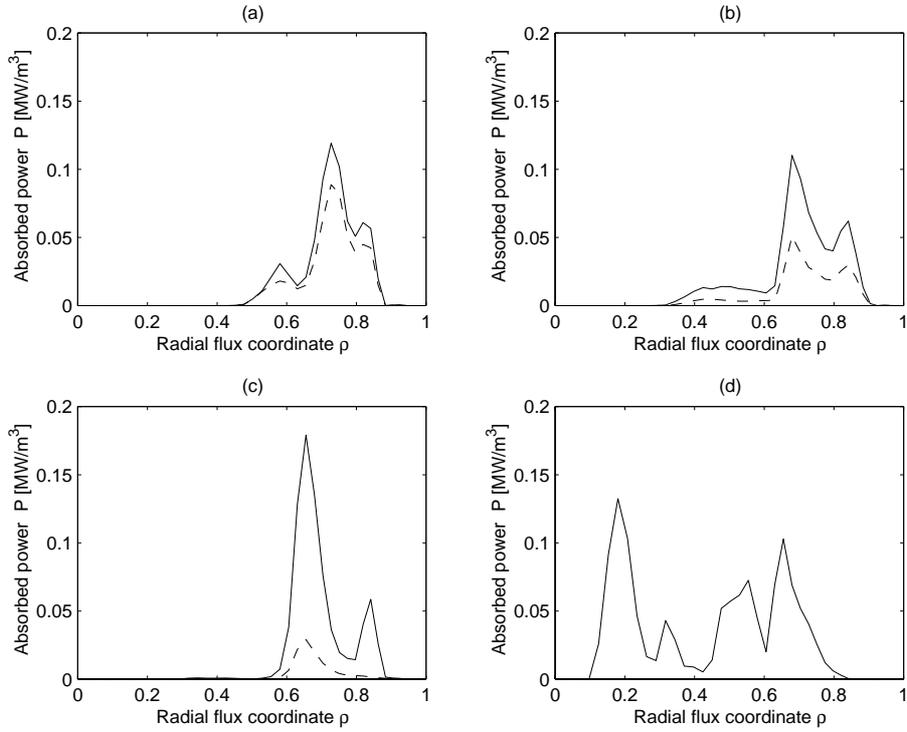


Figure 3. The total absorbed power density (solid line) and the power density absorbed as a fast wave (dashed line) in an ITER-like tokamak when $n_{\phi 0} = 2.0$. The central densities are:

(a) $n_{e0} = 2 \times 10^{20} \text{ m}^{-3}$, (b) $1.3 \times 10^{20} \text{ m}^{-3}$, (c) $1.0 \times 10^{20} \text{ m}^{-3}$, (d) $0.6 \times 10^{20} \text{ m}^{-3}$.

3. Effect of mode transformation on power deposition

We now analyse the effect of mode transformation on power deposition in an ITER-like tokamak with the parameters described above. In contrast to the previous section, we now consider a non-circular plasma with elongation $\kappa = 1.6$ and triangularity $\delta = 0.4$. The launched LH power is 50 MW, and a deuterium–tritium (50:50) plasma is assumed. The power deposition profiles were calculated with the Fast Ray-Tracing Code `FRTC` [5].

The total absorbed power and the power absorbed as a fast wave are illustrated in Fig. for different values of the initial toroidal refractive index $n_{\phi 0}$. As is expected, the amount of mode transformation increases when the initial toroidal refractive index becomes smaller. When we have $1.6 \lesssim n_{\phi 0} \lesssim 2.0$, the contribution of the fast wave to the deposited power is significant. At large values of the toroidal refractive index ($n_{\phi 0} \gtrsim 2.2$), the effect of the fast wave is not important.

The mode transformations are rare at high values of $n_{\phi 0}$ because the accessibility regions of the slow and the fast wave are almost separate at the Golant-Stix boundary. Furthermore, it is easier for the wave to reach the mode transformation surface of Fig. if the initial value of the parallel refractive index is not too large.

The effect of the electron density on the power deposition profiles is illustrated in Fig. when the toroidal refractive index is $n_{\phi 0} = 2.0$. The contribution of the fast wave to the deposited power clearly increases with increasing density. At the very high central density of $n_{e0} = 2 \times 10^{20} \text{ m}^{-3}$, most of the power deposition occurs when the LH wave is a fast wave. At low central densities ($n_{e0} \lesssim 0.8 \times 10^{20} \text{ m}^{-3}$), all the lower hybrid power is absorbed as a slow wave.

The observed increase in the fast wave deposition with increasing plasma density is in agreement with the results obtained in Sec. 2. The mode transformation surface presented in Fig. is located at higher values of n_{\parallel} when the central plasma density is high, which makes mode transformation more probable.

In conclusion, we have considered the effect of the mode transformed fast wave on the power deposition profiles in lower hybrid current drive. The contribution of the fast wave to the deposited power was found to increase with decreasing toroidal refractive index of the launched wave. The contribution of the fast wave to the deposited power also increased with increasing plasma density. At high densities, the fast wave was found to dominate the absorption process.

References

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