LOWER HYBRID CURRENT DRIVE EFFICIENCY IN ASDEX

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The ASDEX lower hybrid current drive experiments at 1.3 GHz have been re-evaluated in view of a new analytic model for the current drive efficiency in the presence of a dc electric field /1/. This model is based on a perturbation solution of the adjoint problem to the Fokker Planck equation and includes the effects of a dc electric field and of a finite width of the wave spectrum. The current drive efficiency I_{RF}/P_{RF}, normalized to its value $(I_{RF}/P_{RF})_o$ at zero electric field, is then given by

$$\eta/\eta_o = \frac{I_{RF}/P_{RF}}{(I_{RF}/P_{RF})_o} = \frac{\ln((1 - X_1)/(1 - X_2))}{X_2 - X_1} \qquad (1)$$

where $X_{1,2} = \alpha\, E_N\, u^2_{1,2}$ with $\alpha = 12/(Z+7)$, $E_N = E/E_{Dr}$, $u = v_{ph}/v_{th}$, $E_{Dr} = m_e v_{th} \nu_o/e$ and $\nu_o = n_e\, e^4 \ln\Lambda/2\pi\, \varepsilon_0^2\, m^2\, v_{th}^3$. The indices correspond to the limits v_{ph1} and v_{ph2} of the wave phase velocity spectrum. The normalized efficiency, equ. (1), is shown in Fig. 1 for various values of $(X_2/X_1)^{1/2}$, i.e. the width of the spectrum. The efficiency is seen to depend mainly on X_2, corresponding to the high phase velocity boundary of the spectrum. Its dependence on X_1 is rather weak.

For the limiting situation of a very broad spectrum, $X_2/X_1 \to \infty$, equ. (1) becomes nearly independent of X_1 and can be approximated as

$$\eta/\eta_o = - \ln |1-X_2|/X_2 \ . \qquad (2)$$

In the opposite situation of a narrow spectrum with $X_1 = X_2 = X$ we get

$$\eta/\eta_o = 1/(1-X). \qquad (3)$$

In the ASDEX-experiments the plasma current I_p was feedback controlled. The measured quantities are the net RF power P_{RF}, the line averaged electron density n_e, and the rate of change of the primary current I_{OH} in the

OH-transformer which is necessary to maintain a constant plasma current. $I'_{OH,OH}$ is its value just before the application of the RF-power, $I'_{OH,RF}$ its value during applied RF-power. Their ratio is shown in Fig. 2 as a function of RF-power for different densities. From Thomson scattering we obtained the variation of the central electron temperature T_{eo} as a function of P_{RF} and n_e, shown in Fig. 3. Using a measured electron density profile we determined the accessibility condition, $N_{\parallel acc}$, to the central region of the plasma by means of a raytracing code.

The plasma current can be written as the sum of an inductively driven current, for which we assume Spitzer conductivity, and an RF-driven current,

$$I_p = I_{Ind} + I_{RF} \;. \tag{4}$$

From our measurements the RF-driven current can be determined as

$$I_{RF} = I_p \left[1-(I'_{OH,RF}/I'_{OH,OH})\cdot(T_{e,RF}/T_{e,OH})^{1.5}\right] . \tag{5}$$

The temperature correction in this equation takes care of the variation of the Spitzer conductivity due to additional bulk electron heating by the RF-power, which is obtained from Fig. 3. The quantity X_2 is calculated from

$$X_2 = \alpha\, E_N\, u_{acc}^{\;2} = 580 \cdot \alpha\, E/(N_{\parallel acc}^{\;2}\, n_e) \tag{6}$$

in the units V/m, 10^{12} cm^{-3}, with $E = -\,M\, I'_{OH,RF}/2\pi R$ and $M = 80$ µH for ASDEX. For the current drive efficiency at zero electric field we use our old experimental results of reference /2/

$$(I_{RF}/P_{RF})_o = a\cdot\mu\cdot g/n_e \;, \tag{7}$$

where μ describes the fraction of accessible power, g is the theoretical dependence of the efficiency changing with $N_{\parallel acc}$, and a is a numerical fit parameter good up to densities of $n_e \approx 1\cdot10^{13}$ cm^{-3}.

In Fig. 4 we show the resulting experimental current drive efficiencies. For the determination of X_2 we took Z = 3. Comparing Figs. 1 and 4 we find a reasonable agreement. We should, however, not forget that the above model assumes homogeneous profiles for both current density and power absorption, complete power absorption by the fast electrons and that the central value calculated for v_{phacc} is the right value to substitute for $v_{ph\,2}$.

We may also compare our results in the form of the conversion efficiency P_{el}/P_{RF} as defined by N. Fisch and C. Karney, /3/, where for our situation

$P_{el} = - M\, I'_{OH,RF}\, I_{RF}$. Taking the theoretical zero electric field efficiency

$$\eta_o = \beta(u_2^2-u_1^2)/\ln(u_2/u_1)\ , \tag{8}$$

where $\beta = 4/(Z+5)$, the conversion efficiency becomes

$$\frac{P_{el}}{P_{RF}} = -E\,\frac{I_{RF}}{P_{RF}} = -E_N\,\frac{\eta}{\eta_o}\,\eta_o = \frac{2\beta}{\alpha}\cdot\frac{\ln|(1-X_2)/(1-X_1)|}{\ln(X_2/X_1)} \tag{9}$$

This is shown as the solid lines in Fig. 5 as a function $X_2^{1/2} = (\alpha/2)^{1/2}\cdot u_{R2}$ with $u_R = v_{ph}/v_R$ and $v_R = v_{th}/(2\,E_N)^{1/2}$. We have confirmed that for the case of a localized spectrum, $X_2/X_1 = 1$, and for $Z = 1$, equ. (9) agrees very well with the numerical result of N. Fisch and C. Karney, /3/, except for the factor $2\beta/\alpha$ which is only close to, but not exactly unity. We see from Fig. 5 that the conversion efficiency is significantly degrated with increasing spectrum width X_2/X_1.

In Fig. 5 we have also plotted $P_{el}/P_{RF} = -M\, I'_{OH,RF}\, I_{RF}/P_{RF}$ for our experimental points from Fig. 4. Taking $Z = 3$ these points fit to curves in the range $(X_2/X_1)^{1/2} = 16$ to 32. This seems very high. However, we note that the empirical fit factor a in the steady state current drive efficiency is about a factor of two lower than estimated from theory /2/. If we include an absorption coefficient of ≈ 0.5, as was done in the evaluation of the PLT experiments, /4/, the points would fit to curves around $(X_2/X_1)^{1/2} \approx 4$, which seems much more realistic.

References:

/1/ K. Yoshioka, T. Okazaki, F. Leuterer, N. Fujisawa, Physics of Fluids, to be published (April 1988)

/2/ F. Leuterer, F. Söldner, D. Eckhartt et al. Plasma Phys. and Contr. Fus. 27, 1399 (1985)

/3/ C. Karney, N. Fisch, Phys. Fluids 29, 180 (1986)

/4/ C. Karney, N. Fisch, F. Jobes, Phys.Rev. A 32, 2554 (1985)

Figures:

1. Normalized current drive efficiency as a function of electric field.
2. Normalized primary current rate of change as function of the RF-power.
3. Central electron temprature with and without RF-current drive.
4. Experimental current drive efficiency.
5. Efficiency for conversion of RF-power into electromagnetic energy.

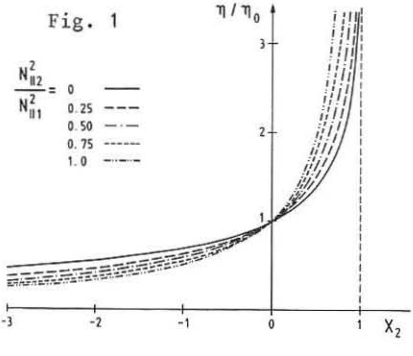

Fig. 1

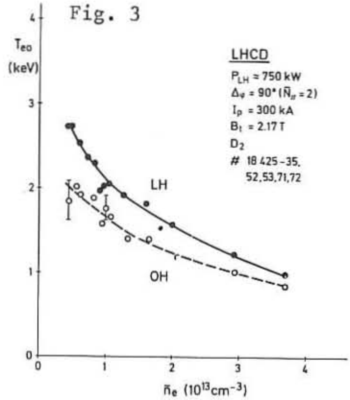

Fig. 3

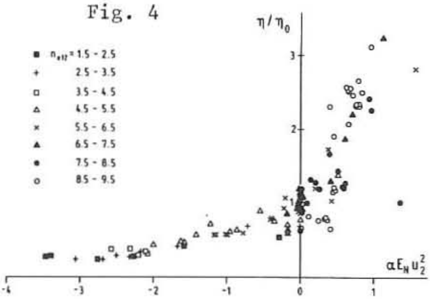

Fig. 4

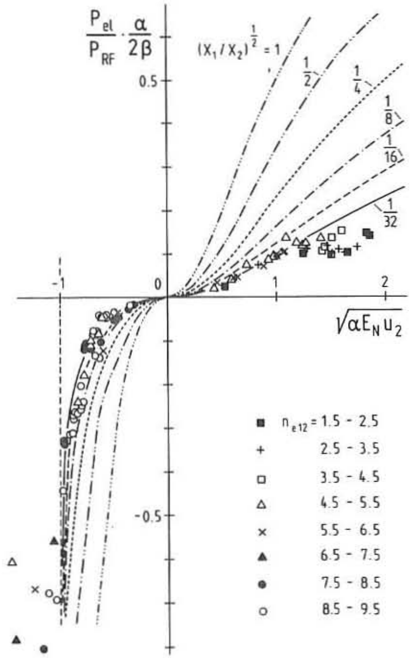

Fig. 5

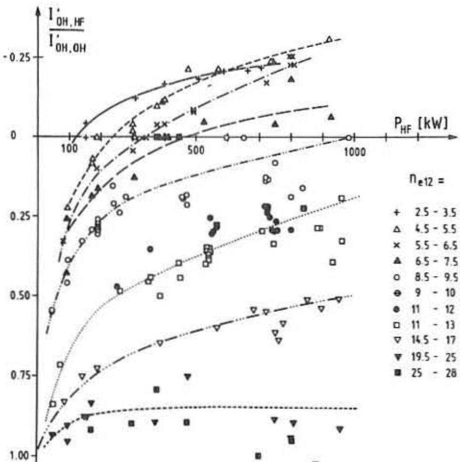

Fig. 2