On Fast Wave Current Drive at Higher Cyclotron Harmonics

A. Hannan, T. Hellsten and T. Johnson.

Euratom-VR Association, EES, KTH, Stockholm, Sweden

Introduction

For steady state operation or long pulses of Tokamak reactors non-inductive current drive is necessary. Even if a large fraction of the current is provided by the bootstrap current, there is still a need for an efficient current drive scheme. Waves in the ion cyclotron range of frequencies can be used for current drive in reactor size plasmas when the waves are damped by transient time magnetic pumping (TTMP) and electron Landau damping (ELD). However, in present day machines this damping is often weak and is in competition with a relatively strong ion cyclotron damping. By operating at higher harmonics of the ion cyclotron frequency the ion absorption can be reduced [1]. However, if the ions are heated up to suprathermal energies, the damping reduces the fast wave current drive efficiency. Here the fast wave current drive efficiency is studied with the newly developed SELFO-light code. SELFO-light calculates the wave field, power deposition and distribution functions of the resonant species self-consistently. The distribution function is calculated with a simplified 1D time dependent Fokker-Planck code [2], combined with a formula for describing the anisotropy [3]. The Fokker-Planck code solves the 1D Fokker-Planck equation using cubic finite element basis functions. The wave field required to calculate the quasi-linear operator for the Fokker-Planck code is calculated with the global full wave code LION [4]. The plasma volume is divided into several sub volumes for which the distribution function is calculated. Self-consistency is obtained by modifying of the susceptibility tensors when calculating the wave field and power partition, by using the non-thermal plasma distribution functions calculated with the Fokker-Planck code. Here we study how the efficiency of the current drive is limited by RF power with and without neutral beam injection.

Fast Wave Current Drive

Fast wave current drive is achieved by heating electrons with a directed wave spectrum. The current is limited by absorption on trapped electrons and collisional transfer of momentum to ions and trapped electrons. This results in current profiles peaked at the magnetic axis where collisionality and trapped particle effects are lowest. In general the competition between ion and electron absorption allows efficient current drive only in regimes where ion absorption is weak. The current drive is calculated from the local power density by an analytic formula [5].

Results and Discussion

Self-consistent calculations of power partition and current drive efficiency have been done to study the effects of frequency f, toroidal mode number n_φ , plasma temperature and density. A comparison of the current drive efficiency between a Maxwellian plasma at $t = 0$ s and a non Maxwellian plasma, close to steady state, at $t = 1$ s is done.

A single specie deuterium plasma or a deuterium plasma with 5% hydrogen is used with $B_0 = 2.08$ T, $R_0 = 2.28$ m, $a = 0.72$ m and $P_{RF} = 10$ MW, $P_{NB} = 10$ MW and neutral beam energy $E_{NB} = 100$ keV. For the pure deuterium plasma the variation of current drive efficiency versus toroidal mode number, n_φ , for $f = 51$ MHz, $n_D = 2.5 \times 10^{19}$ m^{-3} and $T_i = 5$ keV is shown in Fig. 1. For lower values of n_φ the ion cyclotron absorption increases with time because of tail formation of the distribution function. The general trend is that the current drive efficiency decreases with increasing n_φ because of absorption on trapped electrons. It can be seen from Fig. 3 that the self-consistent calculations are important for $n_\varphi < 25$ because of the lower value of $v_{||}$. For $n_\varphi < 21$ more power is absorbed by trapped particles.

A scan is done by keeping the ratio n_φ / f constant for $n_D = 2.5 \times 10^{19}$ m^{-3} and $T_i = 5$ keV. For the pure deuterium plasma the variation of current drive efficiency for $f \geq 3\Omega_D$ is slow, see Fig. 2. At $f \approx 3\Omega_D$ the ion cyclotron absorption increases, resulting in lower current drive efficiency. For the case $n_\varphi = 15$, $f = 45$ MHz the ion power increases up to almost 50 % of the total power, which results in a decrease in the current drive efficiency to almost half of the peak value. The peak value of current drive efficiency is obtained at $n_\varphi = 23$ with $f = 69$ MHz.

For the pure deuterium plasma the fractional power absorbed by electrons and the current drive efficiency versus f for $n_\varphi = 23$, $n_D = 2.5 \times 10^{19}$ m^{-3} and $T_i = 5$ keV is shown in Fig. 3. Starting with 2nd harmonic $2\Omega_D = 34$ MHz at the centre, where almost all the power is absorbed by ions, an increase in f shows a rapid increase in current drive efficiency up to 4th deuterium harmonic $2\Omega_D = 68$ MHz, a further increase in f gives only a slow increase in the current drive efficiency. In this case self-consistent calculations are not very important.

The variation of the current drive efficiency with respect to density and temperature for a pure deuterium plasma has been studied for the case $n_\varphi = 23$ and $f = 69$ MHz, as shown in Fig. 4 and Fig. 5 respectively. In this case self-consistent calculations are not very important. Fig. 5 shows the affect of temperature for $n_\varphi = 23$, $f = 69$ MHz and $n_D = 2.5 \times 10^{19}$ m^{-3} on current drive efficiency. The current drive efficiency increases almost linearly with plasma temperature.

Residual hydrogen in the plasma can reduce the electron absorption. Deuterium plasma with 5% hydrogen is studied for $n_H = 1.25 \times 10^{18}$ m^{-3}, $n_D = 2.5 \times 10^{19}$ m^{-3}, $n_\varphi = 23$ and $T_i = 5$ keV. The fractional powers absorbed by hydrogen, deuterium and electron are plotted versus frequency as shown in Fig. 6(a). Around $f \approx 2\Omega_H$ at plasma center the power absorbed by hydrogen increases significantly up to 60 % of the total power for Maxwellian plasma and up to 80% for steady state non Maxwellian plasma. Self-consistent calculations become important in the presence of residual hydrogen in the plasma, if $f \approx 2\Omega_H$ and $f \approx 3\Omega_H$ are located inside plasma. A plot of current drive efficiency versus frequency is shown in Fig. 6(b). It can be seen that significant correction is required in the value of current drive efficiency when 2nd and 3rd hydrogen harmonics are present in the plasma.

The pure deuterium plasma is studied with the neutral beam injection. Presence of neutral beam results in development of a high-energy tail of deuterium ions, enhancing the RF absorption for the deuterium as shown in Fig. 7(a). This results in a significant decrease of the current drive efficiency for lower frequencies as can shown in Fig. 7(b).

Deuterium plasma with 5% hydrogen is also studied with the neutral beam injection. The presence of neutral beam and the 2nd and 3rd hydrogen harmonic resonances result in significant decrease of the power absorbed by electrons, which leads to a significant reduction of the current drive efficiency as shown in Fig. 8(b).

Conclusions

FWCD has been studied at higher harmonics. For the studied parameters FWCD at frequencies above 3rd harmonic of deuterium and 2nd harmonic of hydrogen is found to be efficient. Low toroidal mode number is desired for efficient current drive. The current drive efficiency increases with plasma temperature because of reduced collisionality. Self-consistent calculations are important at low harmonic numbers and in the presence of minority hydrogen and neutral beam injection.

Acknowledgement

This work has been partly conducted within the GoTiT programme.

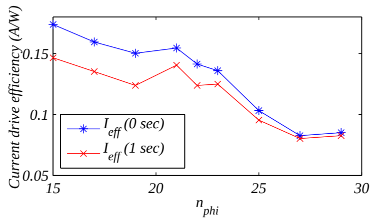

Fig. 1: *Current drive efficiency versus n_φ for f = 51MHz, n_D = 2.5 x 10^{19} m^{-3} and T_D = 5 keV.*

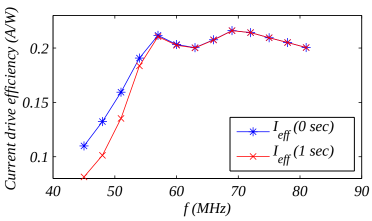

Fig. 2: *Current drive efficiency versus f for constant value of n_φ/f, n_D = 2.5 x 10^{19} m^{-3} and T_D = 5 keV.*

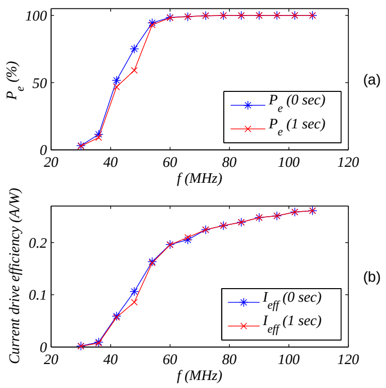

Fig. 3: *(a) Electron power fraction and (b) current drive efficiency versus f for n_φ = 23, n_D = 2.5x10^{19} m^{-3} and T_D = 5 keV.*

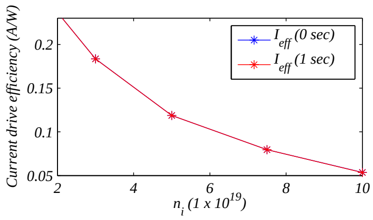

Fig. 4: *Current drive efficiency versus n_i for f = 69MHz, n_φ = 23 and T_D = 5 keV.*

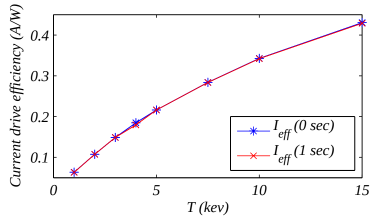

Fig. 5: *Current drive efficiency versus T_i for f = 69MHz, n_φ = 23 and n_D = 2.5 x 10^{19} m^{-3}.*

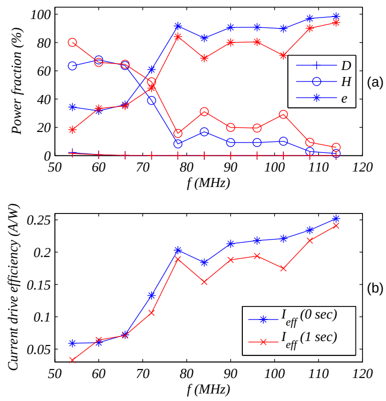

Fig. 6: *(a) Electron power fraction and (b) current drive efficiency versus f for constant value of n_φ= 23, n_D= 2.5x10^{19} m^{-3}, n_H= 1.25x10^{18} m^{-3} and T_i = 5 keV.*

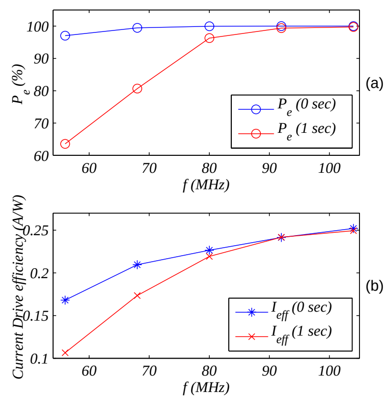

Fig. 7: *(a) Electron power fraction and (b) current drive efficiency versus f for constant value of n_φ= 23, n_D=2.5 x 10^{19} m^{-3}, n_H=1.25 x 10^{18} m^{-3}, T_i = 5 keV, P_{NB} = 10 MW and E_{NB} = 100 keV.*

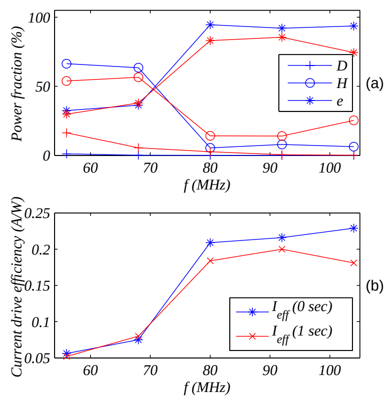

Fig. 8: *(a) Electron power fraction and (b) current drive efficiency versus f for constant value of n_φ= 23, n_D= 2.5x10^{19} m^{-3}, n_H= 1.25x10^{18} m^{-3}, T_i = 5 keV, P_{NB} = 10 MW and E_{NB} = 100 keV.*

References

[1] Petty, C.C. et al, 1995 Nucl. Fusion **35** 773.

[2] Hannan, A. et al, EPS 2010, Dublin.

[3] Anderson, D. et al, Plasma Physics and Controlled Fusion **29** (1987) 891.

[4] Villard, L. et al, Nucl. Fusion, **35**, 1173 (1995).

[5] Chiu, S.C. et al M. Nucl. Fusion, **29** (1989).