DE89 013049

FAST WAVE CURRENT DRIVE MODELING FOR ITER AND PROSPECTS
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Introduction

It is widely recognized that a key element in the development of an attractive tokamak reactor, and in the successful achievement of the mission of ITER is the development of an efficient steady state current drive technique. An important figure of merit in this context is the quantity

$$\gamma = \frac{n_e}{10^{20} m^{-3}} I_{RF} \frac{R}{P_{RF}} = 1.6 \times 10^{-3} T_e \quad \bar{j}/\bar{p} \quad (1)$$

Ehst¹ has provided a simple algebraic expression for $\bar{j}/\bar{p}$ obtained as a fit to Fokker-Planck results of Karney and Fisch² employing a momentum conserving collision operator but not including trapped particle effects

$$\bar{j}/\bar{p} = \frac{8u^2}{5 + Z_{eff}} + 2 + \frac{12(6 + Z_{eff})}{(5 + Z_{eff})(3 + Z_{eff})} + \frac{2D}{Z_{eff}u} \quad (2)$$

where the factor $D = 8.09$ if the dominant damping mechanism is electron TTMP. For parameters projected for the steady state technology phase of ITER values of γ greater than 0.5 are easily achieved for current driven near the magnetic axis. With $Z_{eff} = 2.2$, $\bar{j}/\bar{p}$ given by Eq (2) has a minimum at $u = 1.5$ which at a central temperature of $T_e(0) = 33\text{keV}$ gives $\gamma = 0.35$ from Eq (1). If such values are actually achievable the fast wave current drive would appear to be a very attractive scheme for ITER. The two primary issues to be resolved are:

1. Can an acceptable antenna be designed to produce a $k_{\parallel}$ spectrum with most power in the phase velocity range $v_e < v_{phase} < c$?
2. Will the RF power be efficiently absorbed by electrons in the desired velocity range without unacceptable parasitic damping by fuel ions and α particles?

To address these issues we have employed the ORION code which gives a 3D full-wave solution of the fast wave equations in tokamak geometry along with power absorption and current drive profiles. This 3D code realistically models the launched antenna spectrum with radial focusing, includes toroidal eigenmode effects (multiple pass absorption) if present, and includes the effects of ion cyclotron harmonic and α particle damping.

ITER FWCD Antenna Array

The results presented here are based on a preliminary antenna array design being developed by J. J. Yugo of the Fusion Engineering Design Center and by members of the ORNL Fusion Energy Division Plasma Technology Section. The array consists of 12 individually phased antennas with centers separated

* Research sponsored by the Office of Fusion Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

toroidally by 45 cm. Each antenna consists of 5 poloidally stacked straps to a total poloidal extent of 300 cm. The straps are 22 cm wide, 2 cm thick and are recessed from the first wall by about 8 cm with an additional 10 cm separation between the back of the current strap and the conducting backplane of the antenna enclosure. The antennas are separated by a slotted isolating septum of 2 cm thickness. The model presented here does not include the image currents due to the septa. The model is however being extended to include this effect. Engineering details of the antenna design and its integration into the ITER device will be presented separately by J. J. Yugo.

Description of the 2D Full Wave Model

The 2D full wave code ORION^{3,4,5} solves the vector wave equation for the fast wave fields

$$\nabla \times \nabla \times \mathbf{E} - \frac{\omega^2}{c^2} \mathbf{K} \cdot \mathbf{E} = i\omega\mu_0 \mathbf{J}_{ant} \quad (3)$$

where $\mathbf{K}$ is the dielectric tensor. We use a reduced warm plasma description for the plasma response in which $\mathbf{K}$ is the warm plasma dielectric tensor expanded to 2nd order in Larmor radius. Maxwellian electrons, deuterium and tritium components as well as slowing down alpha particles are included. For the values of $k_{\parallel}$ and $k_{\perp}$ required we approximate $k_{\parallel}$ by $k_{toroidal}$ and obtain $k_{\perp}$ from the fast wave root of the local warm plasma dispersion relation. In this way warm plasma damping effects (cyclotron damping, Landau damping and TTMP) are included and the effect of the presence of the Bernstein wave on the fast wave is approximated, while maintaining a 2nd order differential system. The comparison of this reduced kinetic description with the full 6th order equations (including Bernstein waves) is discussed in ref. 6. From Eq (6) two components of $\mathbf{E}$ perpendicular to $\mathbf{B}$ are solved while $E_{\parallel}$ is obtained from the parallel equation as a perturbation. From $\mathbf{E}$ the local rate of energy deposition is obtained as $\dot{W} = \text{Re}\{\mathbf{E}^* \cdot \mathbf{J}_P\}/2$. The wave parallel phase velocity is $v_{phase} = \omega/k_{\parallel}$ where we approximate $k_{\parallel} = N_T R_{maj}$. Then the current driven by the power in a given toroidal mode is

$$J(N_T) = \text{sgn}(N_T) \frac{19.19 \times 10^{18} T_e(0)}{2\pi R_{maj} n_e(0) \ln \Lambda} \quad \bar{j}/\bar{p} \quad \dot{W}(N_T) \quad (4)$$

where $\bar{j}/\bar{p}$ is given by Eq(1) with $u = \omega/k_{\parallel} v_{th}$. However for $v_{phase} > c$, $J(N_T)$ is taken as zero and to account in a coarse way for trapped particle effects, $J(N_T)$ is also taken as zero for $v_{phase} < v_e$. The total driven current is then the sum over N_T .

ITER Parameters

For purposes of these calculations we have taken ITER parameters as given for the steady state technology phase described in ref. 7. Specifically $R_{maj} = 5.5\text{m}$, $R_{min} = 1.8\text{m}$, $B_0 = 5.3\text{T}$, $I_P = 18\text{MA}$, $\kappa = 2.0$, $\delta = 0.4$. There is an additional 10 cm scrape off region between the plasma and the antenna, and since our models do not allow recessed antennas at this time, we take the wall radius to be at the backplane location, 10 cm beyond the antenna. We have assumed a peak temperature of 33 keV, $\langle T_e \rangle \sim 18\text{keV}$, and peak density $n_e(0) \sim 0.7 \times 10^{20}$, $\langle n_e \rangle = 0.47 \times 10^{20}$ where $\alpha_T = 1.0$, $\alpha_e = 0.5$. Assuming a Troyon g factor of 2.9, with these parameters the β limit is given by (see ref. 8.) $\beta_{max} = g I_P / R_{min} B_0 = 5.5\%$. The thermal component is (using the notation of

ref. 8) $\beta_{th} = 0.4n_{20}T_{10}(1 + n_i/n_e)/B_0^2 \simeq 2.5\%$, while the fast alpha component is $\beta_{f\alpha} = 0.29(n_{DT}/n_e)^2(T_{10} - 0.37) \simeq 0.6\%$. Thus $\beta_{total} \simeq 3.1\% < \beta_{max}$. Also in accordance with the guidelines of ref. 8, we have taken $Z_{eff} = 2.26$ appropriate to a 10% thermal α fraction.

ITER Results

Fig (1a) shows the spectrum of absorbed power (solid curve, the dashed curve is the absorption spectrum unweighted by the antenna spectrum) expressed in terms of $k_{||}$ on the magnetic axis, for a relative phasing between elements of -0.45π . This phasing was found to give maximum efficiency for this configuration. The spectrum is seen to be well peaked about $n_{||} \simeq -2.45$ with very little power propagating in the opposite direction. The net efficiency is $I/P_{Tot} = 0.131$ A/W ($\gamma = 0.33$) where P_{Tot} is the total power launched into the plasma [i.e. the integral of Fig(1a)]. Fig (1b) shows contours of power deposition in the midplane of the antenna obtained from the ORION code. The circular region around the axis is TTMP/ELD on the electrons whereas the vertical strip to the left is ion absorption at the tritium 2nd harmonic. In this case 89% is absorbed by the electrons and 11% is absorbed by tritium. Essentially none is absorbed by α particles. Fig(1c) shows the flux surface average absorbed power profile. The driven current profile follows the electron absorption profile closely.

Possibilities for a FWCD Proof-of-Principle Experiment

A critical need in this field is for a clean proof-of-principle experiment on a large hot tokamak. A very attractive candidate is D-III-D where a proposal has been made and a collaborative effort has begun between GA and ORNL to design an appropriate antenna array and perform such experiments. With 2MW of ECH power, it is anticipated that the high central electron temperatures needed for good electron absorption and high current drive efficiency can be obtained on D-III-D. For these calculations we have assumed a peak temperature of 7 keV and peak density $n_e(0) \sim 0.2 \times 10^{20}$, $R_{maj} = 1.67$ m, $R_{min} = 0.63$ m, $B_0 = 1.0$ T. The antenna consists of 4 current straps of width 11 cm and center-to-center separation of 23 cm. With ORION toroidal eigenmodes are seen in $k_{||}$ which make the current drive efficiency somewhat sensitive to the array phasing. In this case optimum efficiency was obtained with $\Delta\phi = \pi/2$. The net current drive efficiency was $I/P_{Tot} = 0.42$ A/W which gives $\gamma = .093$.

Conclusions

These calculations suggests that it is indeed possible to obtain the needed spectral control to efficiently drive current in an ITER scale device. The requirements on central temperature for high values of γ , while stringent, are common to all current drive strategies. Such high electron temperatures assure absorption of the fast waves by electrons. Clearly to proceed with confidence to an ITER scale current drive system based on fast waves, a convincing experiment is needed on a major existing tokamak. Our calculations indicate that such a proof-of-principle experiment is feasible on D-III-D.

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Fig. 1.(a) Absorbed power weighted by antenna spectrum (solid) and unweighted (b) Contours of power deposition (c) Flux surface average of power absorbed, total (solid), electrons (dashed).

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