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ELECTRON ABSORPTION OF FAST WAVES IN GLOBAL WAVE CALCULATIONS

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Abstract—The results of a theoretical study of fast wave electron absorption are presented. Proper expressions for the parallel component of the fast wave electric field $E_{\parallel}$ and the electron absorption power, which can be used for global wave calculations, are derived. Electron absorption terms such as transit time magnetic pumping (TTMP), Landau damping and cross-term absorption are all shown to be of the same order of magnitude and should be taken into consideration. Wave equations are written in a form that incorporates electron absorption. Numerical results via the FASTWA code for the Phaedrus-T Tokamak illustrate the typical 3-D structure of the wave electric field and absorbed power, and the relation between different absorption mechanisms for a realistic Tokamak configuration.

1. INTRODUCTION

FAST WAVE ICRH is presently one of the most powerful methods of plasma heating in Tokamaks (see, for example, START *et al.*, 1989). Although many properties of fast magnetosonic waves are well known for homogeneous plasmas in homogeneous magnetic fields, many problems arise when one tries to incorporate realistic properties of Tokamaks such as inhomogeneity, toroidicity or finite size. The WKB approximation which is usually used for high-frequency waves is not uniformly valid in the ion cyclotron range of frequencies because the effects of diffraction and wave interference are very significant.

The first global fast wave simulations of ICRH (COLESTOCK and KLUGE, 1982; ITOH *et al.*, 1984; JAEGER *et al.*, 1986; VILLARD *et al.*, 1986) used the cold plasma approximation. An artificial collision frequency ν was included usually be the replacement $\omega \rightarrow \omega + i\nu$ to resolve the ion–ion hybrid resonance. This approach only works numerically when ν is chosen to be sufficiently large, usually $\nu/\omega \approx 0.01$. This value is much higher than real damping from collisions. If ν is reduced, the computation time increases sharply and numerical errors build up. Such high values of ν are usually extended to the entire plasma volume. However, for ICRH the frequency ω is close to the ion cyclotron frequency Ω_i and such an approach can lead to an incorrect description of the cyclotron wave absorption, so the region where ν is not zero should be narrow (MOROZ, 1987).

In order to incorporate realistic hot plasma effects a method of 3-D calculation was developed (SMITHE *et al.*, 1987), in which power deposition in the plasma was determined via the anti-Hermitian part of a truncated hot plasma dielectric operator.

Fast wave absorption was considered in the literature in more detail for one-dimensional inhomogeneities, where the first- and second-order FLR corrections were included (MCVEY *et al.*, 1985; JAEGER *et al.*, 1988; BRAMBILLA, 1989). These corrections may be essential for the ions. For the electrons they are too small (they are less than the main terms by a factor of ρ_e/L or ρ_e/λ, where ρ_e is the electron Larmor radius, L is the inhomogeneity scale length and λ is the wavelength) and have a negligible effect on the fast wave. As the result, these electron corrections were omitted in this paper to avoid unnecessary excessive complications of the 3-D case.

Global wave calculations taking the electron absorption into account have been published in BRAMBILLA and KRUCKEN (1988), but the expression for the parallel component of the wave electric field $E_\parallel$ neglects the term with $B_\parallel$. This leads the authors to the conclusion that fast wave TTMP is much stronger than Landau damping (in a numerical example, in that paper, $P_{\mathrm{MP}} \approx 4.4\%$ whilst $P_{\mathrm{LD}} \approx 0.1\%$), which differs essentially from the results of this paper. In a recent paper (HELLSTEN and ERIKSSON, 1989), the authors have used Stix's plane-wave model results (STIX, 1975) as part of a modified version of the global wave code LION. Comparison with an experiment (ERIKSSON and HELLSTEN, 1989) leads to the conclusion that their calculations gave a realistic value for the power absorbed by the electrons. However, the problem is that the wave vector $\mathbf{k}$ and hence the y-direction and E_y component are not known in global wave calculations.

Here we present a consistent method to incorporate electron absorption into a global fast wave consideration and perform the results of 3-D calculations via the FASTWA code (MOROZ and COLESTOCK, 1990; MOROZ *et al.*, 1990) for the Phaedrus-T Tokamak. The numerical calculations intend to illustrate the fast wave field and absorbed power distributions, and the relation between the different absorption mechanisms in a realistic Tokamak configuration. The FASTWA code uses the method of Fourier decomposition into toroidal and poloidal modes as in SMITHE *et al.* (1987), but was developed for an arbitrarily-shaped plasma column and includes toroidicity. The power absorbed by different mechanisms such as fundamental ion cyclotron absorption, second-harmonic cyclotron absorption, mode conversion, electron transit time magnetic pumping (TTMP) and cross-term absorption is calculated using the hot plasma dielectric operator. In this paper, attention is focussed only on electron absorption. The main goal was to derive proper expressions for the parallel component of the wave electric field $E_\parallel$ and for the electron absorption terms, which should be independent of the coordinate system and convenient for the global wave calculations.

Correct consideration of $E_\parallel$ and the power absorbed by the electrons is especially important when ion absorption is not large or for fast wave current drive applications.

2. PLANE WAVE IN AN HOMOGENEOUS PLASMA

In the limit in which the plasma and the magnetic field are taken to be homogeneous and infinite, one can consider the penetration of a fast wave with given frequency ω and wave vector $\mathbf{k}$. The wave energy can be absorbed by resonant electrons whose longitudinal velocity is equal to the longitudinal phase velocity of the fast wave $\omega = k_\parallel \cdot v_\parallel$ due to the Cherenkov mechanism. Often in the literature this wave damping is considered as two separate mechanisms. One is Landau damping (LD), in which the force acting on electrons is

$$F_{\mathrm{LD}} = \mathbf{e}_{\|} \cdot q\mathbf{E}, \tag{1}$$

and another is transit time magnetic pumping (TTMP), in which the force is

$$F_{\mathrm{MP}} = -\mathbf{e}_{\|} \cdot \nabla(\mu \cdot B_{\|}). \tag{2}$$

Here q and μ are the charge and the magnetic moment of an electron, and $\mathbf{e}_{\|} = \mathbf{B}_0/B_0$ is the unit vector in the direction of external magnetic field $\mathbf{B}_0$. It has been shown (NAZAROV *et al.*, 1963; PERKINS, 1972; CANOBBIO, 1972) that both processes are effective in fast wave damping. These processes are two aspects of the same Cherenkov mechanism and hence are coherent and so the cross-term should also be incorporated. The result of such an analysis (STIX, 1975) was the cancellation between the TTMP and cross-term absorption.

Using the anti-Hermitian part of the hot plasma dielectric operator $\overleftrightarrow{\varepsilon}^{\mathrm{a}}$, one can calculate the local power deposition

$$P_{\mathrm{abs}} = \int_{-\infty}^{\infty} P \, \mathrm{d}k_{\|} = \frac{\omega}{8\pi} \int_{-\infty}^{\infty} \mathbf{E}^* \cdot \overleftrightarrow{\varepsilon}^{\mathrm{a}} \cdot \mathbf{E} \, \mathrm{d}k_{\|}. \tag{3}$$

The absorbed power P is the sum of the power going to mode conversion, and the ion P_{i} and electron P_{e} absorption of the fast wave. The latter can be divided in three parts, where P_{MP} is the power absorbed by the TTMP, P_{LD} is the Landau damping, and P_{CR} is cross-term absorption

$$P_{\mathrm{e}} = P_{\mathrm{MP}} + P_{\mathrm{LD}} + P_{\mathrm{CR}}.$$

The electrons can also gain some power from fast ion slowing. This process is especially important when the ion distribution function has a large tail. This secondary process is beyond the subject of this paper.

Let us choose the coordinate system in such a way that the z-axis is along the magnetic field and the wave fields have the form

$$\mathbf{E}, \mathbf{B} \sim \exp(-\mathrm{i}\omega t + \mathrm{i}k_{\perp}x + \mathrm{i}k_{\|}z). \tag{4}$$

Then the electron absorption terms become:

$$P_{\mathrm{MP}} = \frac{k_{\perp}^2 v_{\mathrm{e}}^2}{\omega \Omega_{\mathrm{e}}} \cdot G \cdot |E_y|^2 \tag{5}$$

$$P_{\mathrm{LD}} = 2 \cdot \frac{\omega \Omega_{\mathrm{e}}}{k_{\|}^2 v_{\mathrm{e}}^2} \cdot G \cdot |E_z|^2 \tag{6}$$

$$P_{\mathrm{CR}} = 2 \cdot \frac{k_{\perp}}{k_{\|}} \cdot G \cdot \mathrm{Im}\,(E_y^* E_z) \tag{7}$$

where

$$G = \frac{\omega_{pe}^2}{\omega\Omega_c} \cdot \frac{\omega^2}{8\pi k_\| v_e} \cdot \operatorname{Im} Z\left(\frac{\omega}{k_\| v_e}\right). \tag{8}$$

Here ω_{pe} and Ω_c are the electron plasma and cyclotron frequencies, v_e is electron thermal velocity, and Z is the plasma dispersion function.

The fast wave electric field components are related to each other by the expression

$$E_z = -\frac{i}{2} \cdot \frac{k_\perp v_e}{\Omega_c} \cdot \frac{k_\| v_e}{\omega} \cdot E_y - \frac{n_\perp n_\|}{\varepsilon_3} \cdot E_x, \tag{9}$$

which directly follows from Maxwell equations for plane waves in a hot plasma. Here

$$n_\perp = k_\perp/k_0, \quad n_\| = k_\|/k_0, \quad k_0 = \omega/c \tag{10}$$

$$\varepsilon_3 = 1 + 2\frac{\omega_{pe}^2}{k_\|^2 v_e^2}\left[1 + \frac{\omega}{k_\| v_e} \cdot Z\left(\frac{\omega}{k_\| v_e}\right)\right]. \tag{11}$$

If the condition

$$\beta_e \gg \frac{\omega}{\Omega_e}\left(1 + \frac{k_\|^2 v_e^2}{\omega^2}\right) \tag{12}$$

is valid then the last term on the right side of (9) is smaller than the first one. Omitting it we get Stix's relations (STIX, 1975) for electron absorption

$$P_e = P_{LD} = P_{MP}/2. \tag{13}$$

3. GLOBAL WAVE CONSIDERATION

The above relations for the absorbed power show that one can express the electron absorption in terms of only the perpendicular component of the wave electric field E_y. This seems useful for global fast wave calculations where $E_\| = 0$ is the usual approximation. However, the problem is that in global wave calculations the vector $\mathbf{k}_\perp$ and hence the E_y component are not known. Usually only the value of $k_\perp^2$ is determined by the dispersion relation for the fast wave.

In this paper we neglect the effects (PERKINS, 1977) of magnetic field variation along the field lines (poloidal magnetic field effects) on the fast wave penetration and absorption in a Tokamak plasma. These effects can influence the ion cyclotron absorption of a fast wave at low $k_\|$ (KOVRIZHNYKH and MOROZ, 1985; GAMBIER and SAMAIN, 1985; SMITHE *et al.*, 1988; BRAMBILLA, 1989) when

$$k_\| < \Delta l_{res}^{-1} \tag{14}$$

where

$$\Delta l_{res} = \left(\frac{\rho_i B^2}{\mathbf{B} \cdot \nabla B}\right)^{1/2}. \tag{15}$$

We leave the consideration of these effects in the global wave code for future work. However, our estimations show that they are not really essential for fast wave electron absorption. In this situation the longitudinal component of the wave vector $k_\parallel$ is defined through the toroidal component of the wave vector k_φ, and the full wave structure can be calculated by the Fourier composition of solutions for different k_φ.

Our starting point for finding $E_\parallel$ through the $\mathbf{E}_\perp$ and $B_\parallel$ components of the fast wave will be the longitudinal projection of Maxwell equations

$$\mathbf{e}_\parallel \cdot (\nabla \times \mathbf{B}_\perp) = -\mathrm{i}k_0 \mathbf{e}_\parallel \cdot (\overleftrightarrow{\varepsilon} \cdot \mathbf{E}) \tag{16}$$

$$\mathbf{e}_\parallel \cdot (\nabla \times \mathbf{E}_\perp) = \mathrm{i}k_0 B_\parallel . \tag{17}$$

Incorporating the fact that $E_\parallel$ is small in comparison with $E_\perp$ gives a good approximation

$$\mathbf{B}_\perp = \mathbf{n}_\parallel \times \mathbf{E}_\perp \tag{18}$$

for the fast wave, where $\mathbf{n}_\parallel = n_\parallel \mathbf{e}_\parallel$. Then

$$\mathbf{e}_\parallel \cdot (\nabla \times \mathbf{B}_\perp) = n_\parallel (\nabla \cdot \mathbf{E}_\perp) \tag{19}$$

and instead of (9) one will have

$$E_\parallel = -\mathrm{i}n_\parallel [\gamma B_\parallel - (\nabla \cdot \mathbf{E}_\perp)/k_0 \varepsilon_3] \tag{20}$$

where $\gamma = \omega v_\mathrm{e}^2 / 2\Omega_\mathrm{e} \mathrm{c}^2$.

The electron absorption terms can be expressed in terms of these longitudinal components $E_\parallel$ and $B_\parallel$:

$$P_\mathrm{MP} = 2\gamma G |B_\parallel|^2 \tag{21}$$

$$P_\mathrm{LD} = \frac{1}{\gamma n_\parallel^2} \cdot G |E_\parallel|^2 \tag{22}$$

$$P_\mathrm{CR} = \frac{2}{n_\parallel} \cdot G \cdot \mathrm{Im}\,(B_\parallel^* E_\parallel). \tag{23}$$

The above expressions (20)–(23) are independent of the coordinate system and at the same time can easily be brought to the form of (9), (5)–(7) for the case of plane waves with $k_y = 0$ or to the more general form when the coordinate system is chosen such that $k_y \neq 0$ (JAEGER *et al.*, 1988). Expression (20) is the perturbative treatment of $E_\parallel$ through the known $B_\parallel$ and $\mathbf{E}_\perp$. It is a good approximation for the fast wave because $E_\parallel$ is usually small: $E_\parallel / E_\perp \sim m_\mathrm{e}/m_\mathrm{i}$. Using only the first term in (20)

$$E_\parallel = -\mathrm{i}n_\parallel \gamma B_\parallel , \tag{24}$$

one can easily recover Stix's relations (13). But if condition (12) is not fulfilled, the contribution of the term with $(\nabla \cdot \mathbf{E}_\perp)$ can be essential and so the whole ansatz (20) should be used for the numerical calculations.

4. WAVE EQUATIONS

Global fast wave calculations are based on the wave equations. When the electron absorption is weak in comparison with the ion absorption, it is permissible to exclude the electron terms in these equations. Then the electron absorption P_e can be calculated as previously shown through the perturbatively-found (20) longitudinal electric field $E_\parallel$. Other fast wave components are not affected by the electron absorption.

In the more general situation, especially when the ion cyclotron resonance is placed outside the plasma, one should keep the electron absorption terms in the wave equations. The analysis for the fast wave shows that this can be easily done by using in the wave equations

$$\frac{\partial}{\partial x} x E_\vartheta = \mathrm{i} x B_\varphi + \mathrm{i} \frac{\partial}{\partial \vartheta}\left(-\frac{\varepsilon_2}{\varepsilon} E_\vartheta + \frac{1}{\varepsilon x R} \frac{\partial}{\partial \vartheta} R B_\varphi \right) \tag{25}$$

$$\frac{1}{R} \frac{\partial}{\partial x} R B_\varphi = \mathrm{i}\left(n_\perp^2 E_\vartheta + \frac{\varepsilon_2}{\varepsilon x R} \frac{\partial}{\partial \vartheta} R B_\varphi \right), \tag{26}$$

the value of $n_\perp^2$ corresponding to the fast wave refractive index found from the dispersion relation incorporating the electron contribution

$$(\varepsilon_1 - \alpha_1 \varepsilon_3) n_\perp^4 + [\varepsilon\varepsilon_3(-1 + \alpha_e + \alpha_1 + \alpha_2 - \gamma^2 n_\parallel^2 \varepsilon_3) + \varepsilon_2^2 - \varepsilon\varepsilon_1 + 2\varepsilon_2\varepsilon_3(\gamma n_\parallel^2 - \alpha_2)] n_\perp^2 + \varepsilon_3(\varepsilon^2 - \varepsilon_2^2) = 0. \tag{27}$$

The wave equations (25)–(26) were written in quasi-toroidal coordinates (r, ϑ, φ) and $x = k_0 r$, $\varepsilon = \varepsilon_1 - n_\parallel^2$, $R = R_0 + r\cos\vartheta$. For the components of the dielectric tensor in (25)–(27) the following values were introduced:

$$\varepsilon_1 = 1 + \frac{\omega_{pe}^2}{\Omega_e^2} + \sum \frac{\omega_{pi}^2}{2\omega^2} \zeta_0^i [Z(\zeta_1^i) + Z(\zeta_{-1}^i)] \tag{28}$$

$$\varepsilon_2 = -\frac{\omega_{pe}^2}{\omega\Omega_e} + \sum \frac{\omega_{pi}^2}{2\omega^2} \zeta_0^i [Z(\zeta_1^i) - Z(\zeta_{-1}^i)] \tag{29}$$

$$\alpha_1 = \sum \frac{\beta_i}{4} \zeta_0^i [Z(\zeta_2^i) + Z(\zeta_{-2}^i)] \tag{30}$$

$$\alpha_2 = \sum \frac{\beta_i}{4} \zeta_0^i [Z(\zeta_2^i) - Z(\zeta_{-2}^i)] \tag{31}$$

$$\alpha_e = \beta_e \zeta_0^e Z(\zeta_0^e) \tag{32}$$

where summing is performed over all ion species and $\zeta_n^{i;e} = (\omega - n\Omega_{i,e})/k_\parallel v_{i,e}$. Indices i and e correspond to ions and electrons, and β_i and β_e are the ratios of the kinetic to magnetic pressure for ions and electrons.

In dispersion relation (27), the imaginary part of the term with α_e corresponds to the TTMP, and the imaginary part of the terms with ε_3 and γ gives the Landau damping and cross-term absorption. These effects are coherent and for conditions when (12) is valid one can easily see the above-mentioned cancellation effect. In this case the resulting electron absorption can be expressed by substitution of $\gamma \to 0$, $\alpha_e \to \alpha_e/2$ in (27). Terms with α_1 and α_2 express the ion contribution and are important when the second-harmonic resonance $\omega = 2\Omega_i$ is placed in the plasma.

5. NUMERICAL RESULTS

All numerical calculations were carried out via the FASTWA code which gives the full 3-D picture of fast wave field components and the power absorbed by different plasma species. In this paper we are only interested in electron absorption and so we will only show pertinent plots obtained in a typical run of the code. The parameters of the Phaedrus-T Tokamak for the typical minority heating regime were chosen to be:

$$B_0 = 1.2\ \mathrm{T} \quad \rho = 26\ \mathrm{cm}$$
$$R_0 = 92\ \mathrm{cm} \quad a = 33\ \mathrm{cm}. \tag{33}$$

Here ρ and a are the plasma and the chamber radii. The regime of fast wave heating of a D plasma with 5% H minority was considered at the frequency $f = 18.2$ MHz. The plasma parameters were

$$T_D(0) = 500\ \mathrm{eV} \qquad n_e(0) = 5 \times 10^{13}\ \mathrm{cm}^{-3}$$
$$T_H(0) = 1000\ \mathrm{eV} \quad T_e(0) = 800\ \mathrm{eV}. \tag{34}$$

In the code the density and temperature profiles for different plasma species can be chosen independently, but here for convenience the density and temperature profiles were

$$\frac{n_e(r)}{n_e(0)} = \frac{T_e(r)}{T_e(0)} = \frac{T_i(r)}{T_i(0)} = \begin{cases} \left[1 - \left(\frac{r}{\rho}\right)^{k_1}\right]^{k_2} \cdot (1-\delta) + \delta; & r < \rho \\ \delta; \quad \rho < r < a \end{cases} \tag{35}$$

and $\delta = 0.01$, $k_1 = 4$, $k_2 = 2$.

The antenna in this example consisted of two straps with poloidal extension $\Delta\vartheta = 1$ radian and strap width $w = 5$ cm each at the radius $\rho_a = 28$ cm. Two antenna straps were separated by $\Delta l = 17$ cm and fed out of phase $\Delta\varphi = \pi$.

In Fig. 1 the fast wave resonances and cut-off surfaces are shown. One can see the ion cyclotron resonance $\omega = \Omega_H$ for hydrogen ions which is at the same time the second-harmonic resonance $\omega = 2\Omega_D$ for deuterium ions, the ion–ion hybrid resonance (S), the ion–ion cut-off (L) and the fast-wave cut-off (R). The antenna is sited at the low field side of the torus. In Fig. 2 the distribution of the Re (E_x) fast wave field component is shown in the poloidal cross-section. Solid (dotted) lines mean positive (negative) levels. The separation between contours represents a change of 4

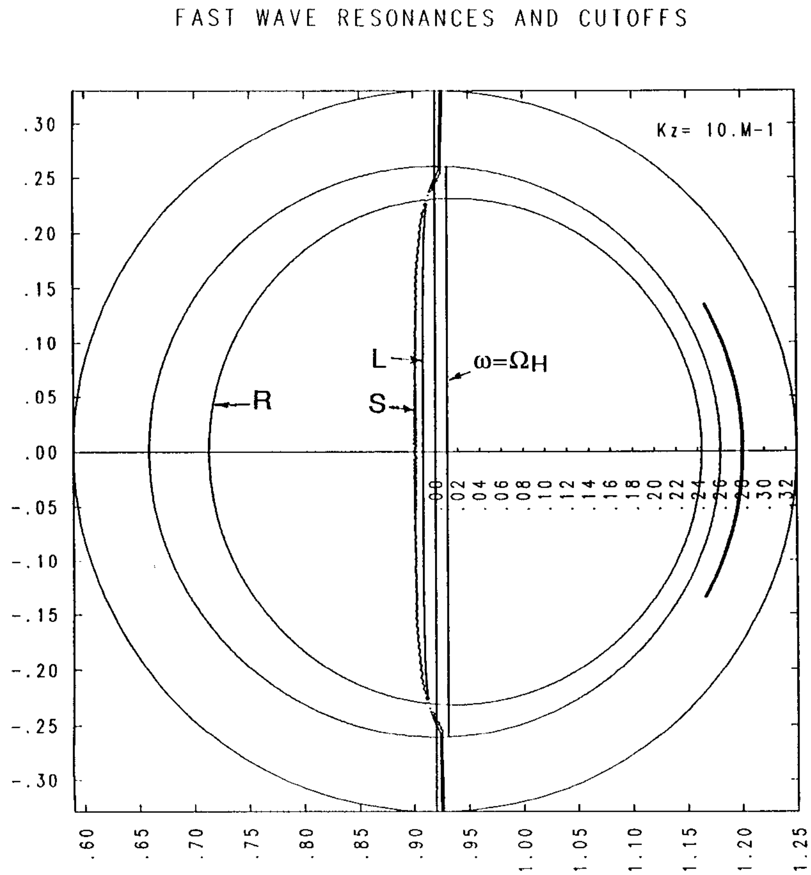

FIG. 1.—Fast wave resonances and cut-offs for the regime considered in the Phaedrus-T D plasma with 5% H minority. The surface S is the ion–ion hybrid resonance, L is ion–ion cut-off and R is the fast wave cut-off. The antenna is positioned at the low magnetic field side of the Tokamak.

V A^{-1} m^{-1}. The units V A^{-1} m^{-1} mean that the electric field is normalized to an antenna current of 1 A. This picture can be used for comparison with the distribution Re $(E_{\|})$ shown in Fig. 3. Here the next contours differ by a value of 6.5 mV A^{-1} m^{-1}. Figure 4 shows the total absorbed power profile in the poloidal cross-section. One can see that most of the power was absorbed near the ion–ion hybrid and ion cyclotron resonances. The power absorbed by electrons has a wider profile and is shown in Fig. 5. The poloidal asymmetry in the plots (Figs 2–5) is the usual characteristic of fast wave penetration and absorption in Tokamaks (see, for example, ITOH *et al.*, 1984) and is the result of gyroasymmetry of the plasma in the magnetic field.

Figure 6 shows the power absorbed by the different species and averaged over the magnetic surfaces. Again, the units W A^{-2} mean that the power is normalized to the power for the 1 A antenna current. P_{tot} and P_{pla} are the amounts of total absorbed r.f. power and power absorbed inside the plasma column, where $\Psi < 1$ [as one can see from (35), there is some low density and low temperature plasma for $\Psi > 1$, so

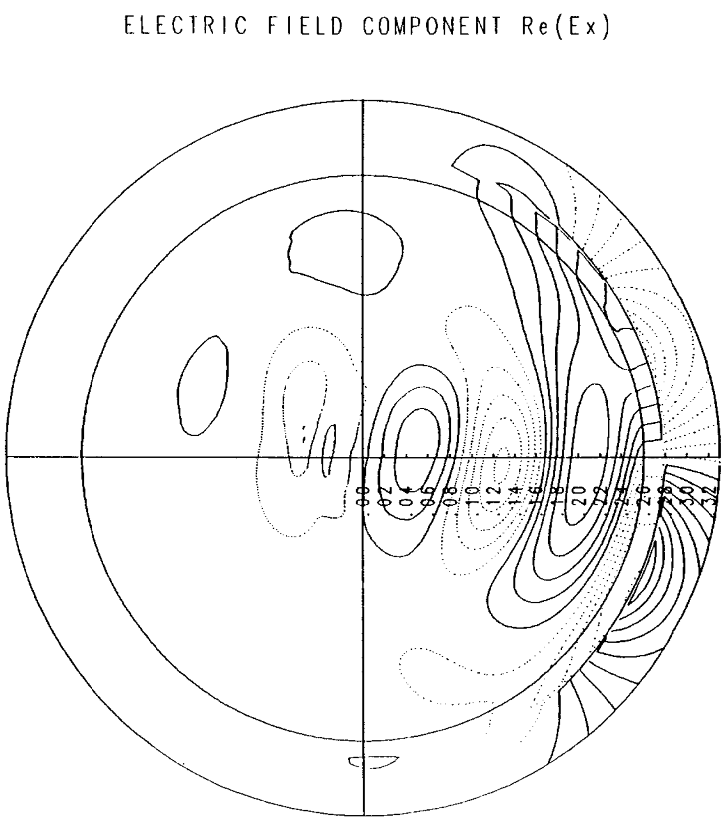

FIG. 2.—Re (E_x) distribution in the poloidal cross-section. The separation between contours represents a change of 4 V A^{-1} m^{-1}.

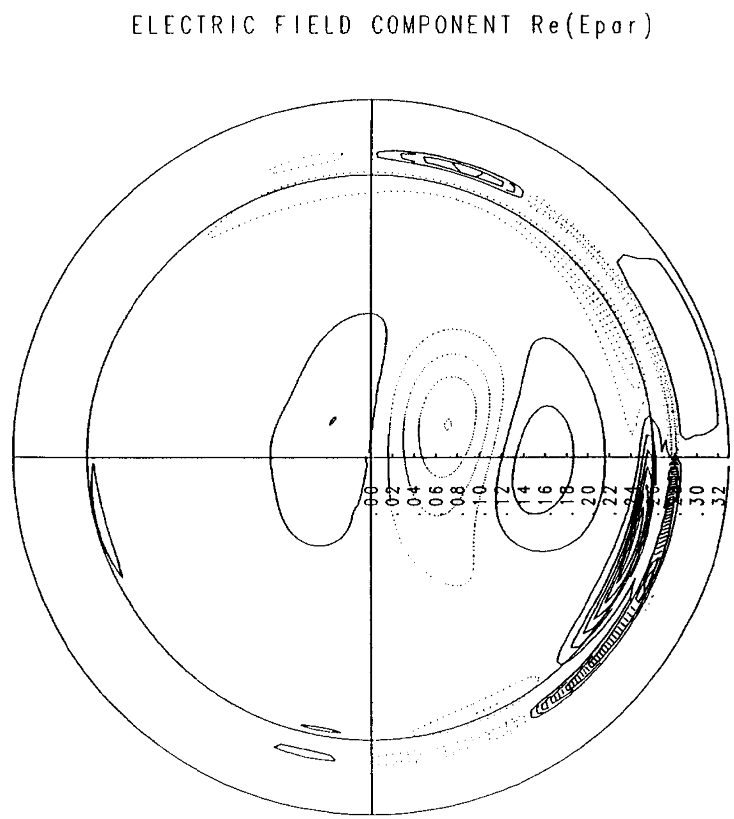

FIG. 3.—Re ($E_\parallel$) distribution in the poloidal cross-section. The separation between contours represents a change of 6.5 mV A^{-1} m^{-1}.

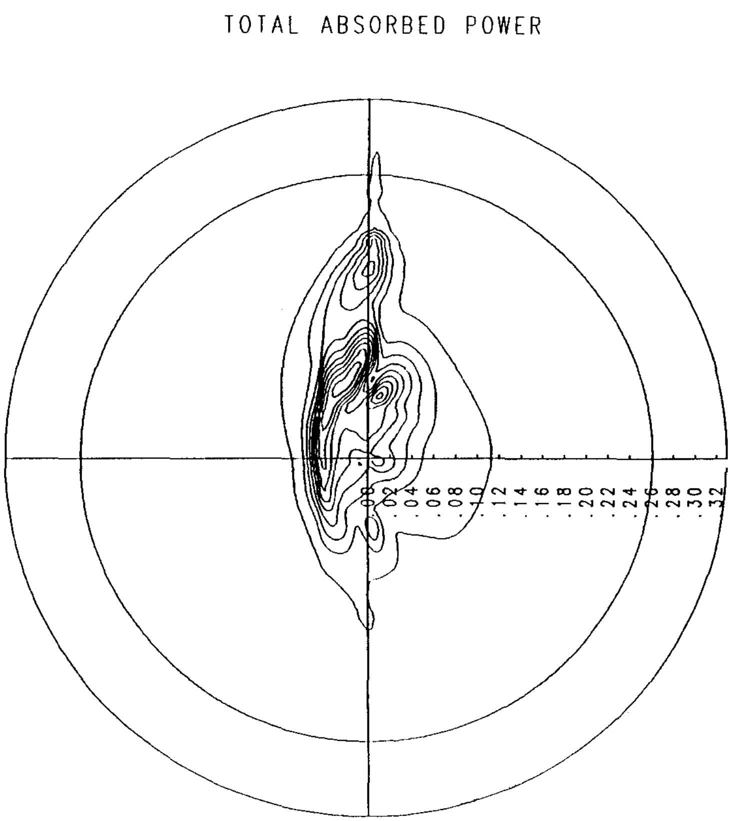

FIG. 4.—Contours of total absorbed power.

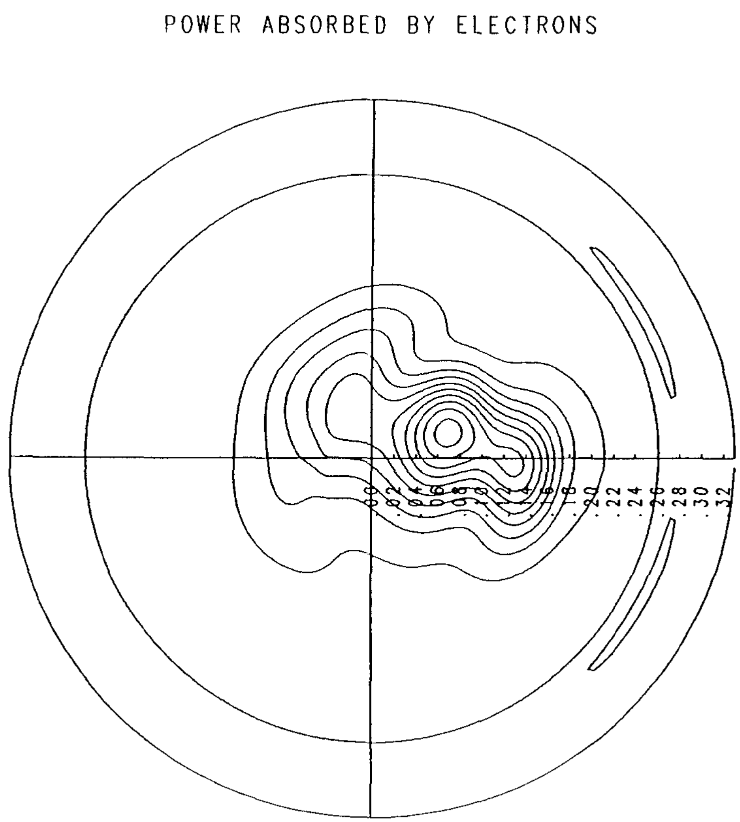

FIG. 5.—Contours of power absorbed by the electrons.

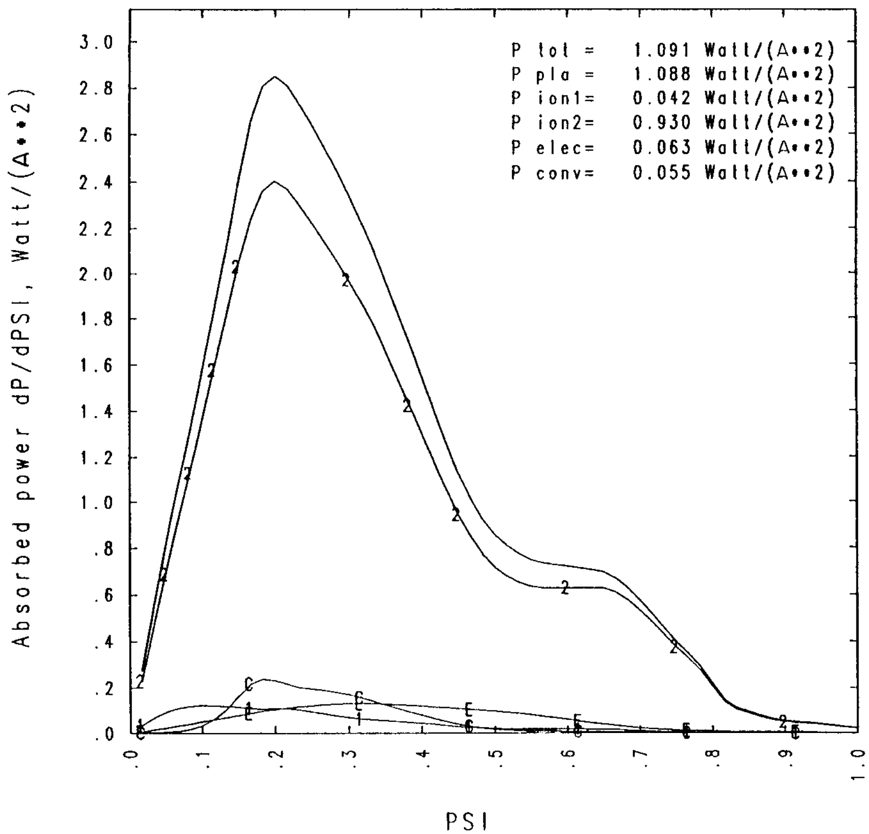

FIG. 6.—The power absorbed by different species and averaged over the magnetic surfaces: 1 is P_D, 2 is P_H, E is P_e and C is mode conversion.

$P_{tot} \geqslant P_{pla}$]. The values of Ψ, generally chosen in the FASTWA code to perform the magnetic surfaces, in the example considered, correspond to the values of r/ρ. P_{ion1}, P_{ion2}, P_{elec} and P_{conv} are amounts of r.f. power absorbed, respectively, by the majority ions (label 1 on the curve), minority ions (label 2), electrons (label E), and the mode conversion process (label C). From Fig. 6 one can see that in the minority heating regime considered, approximately 85% of the total power is absorbed by the minority ions, 6% is absorbed by the electrons, 5% by the mode conversion mechanism, and 4% by the majority ions.

Figure 7 shows the power averaged over the magnetic surfaces and absorbed by the electrons via different mechanisms: TTMP, Landau damping and cross-term absorption. One can see that TTMP and cross-term absorption give opposite contributions and the total electron absorption does not differ too much from the Landau damping.

Figures 8–10 show the top view of the torus. In Fig. 8 the wave component Re (E_R) directed along the major radius is concentrated in the part of the torus close to the antenna. This is true for other fast wave components but not $E_\parallel$. In Fig. 9 one can see that Re ($E_\parallel$) has a good penetration along the torus. The straight line in Fig. 8

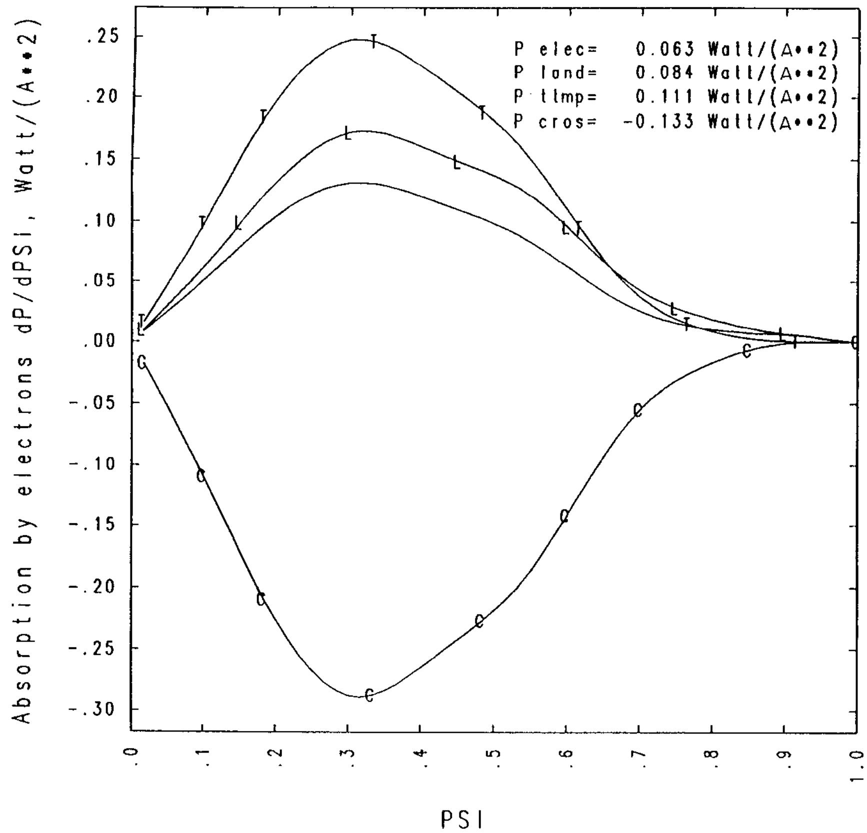

FIG. 7.—The power absorbed by different electron mechanisms: T is P_{MP}, L is P_{LD} and C is P_{CR}.

shows the poloidal cross-section chosen for Figs 2 and 3. The last figure, Fig. 10, shows the contours of total absorbed power in the torus. At the right side of the picture one can see the two-strap antenna.

6. DISCUSSION AND CONCLUSIONS

During ICRF fast wave plasma heating the r.f. power goes to both the ions and electrons. Electrons can gain r.f. power in three ways—direct fast wave absorption by electrons, transferring the energy from fast ions appearing during ICRH, and electron absorption of the slow wave after the mode conversion process. This paper is devoted only to direct electron absorption of the fast wave which can be divided in three coherent parts—TTMP, Landau damping and cross-term absorption. These three parts were analyzed here in a plane-wave model and in a global-wave consideration. The $E_{\parallel}$ component was calculated perturbatively through the $B_{\parallel}$ and $E_{\perp}$ components. The expressions derived are independent of the coordinate system and convenient for 3-D computations. Electron absorption analysis has been included in the "order reduction" scheme of the global wave code FASTWA. TTMP and cross-term electron absorption terms give opposite contributions. Numerical calculations

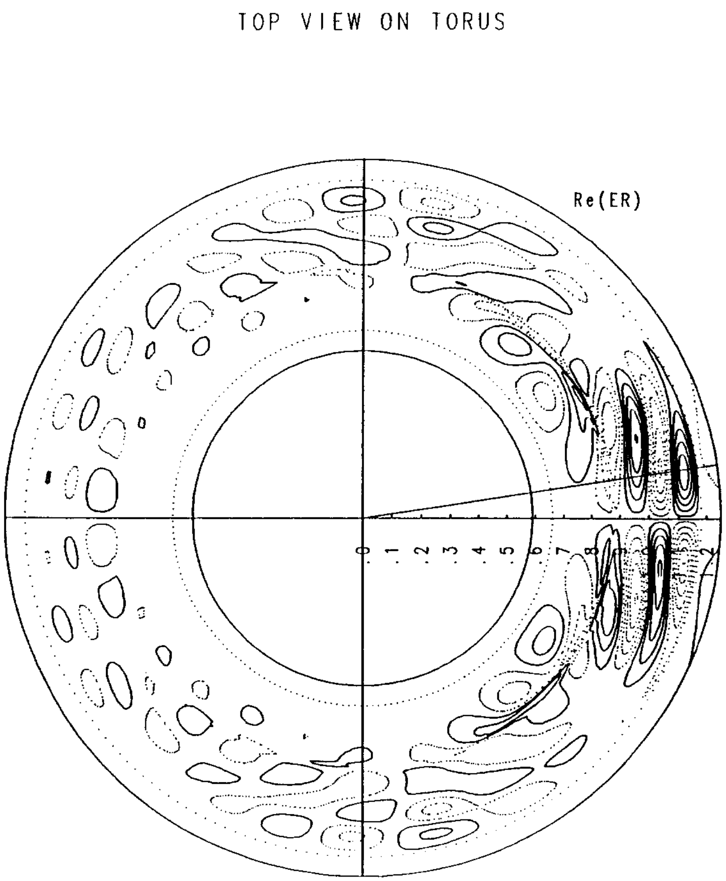

FIG. 8.—Top view on the torus. Re (E_R) distribution.

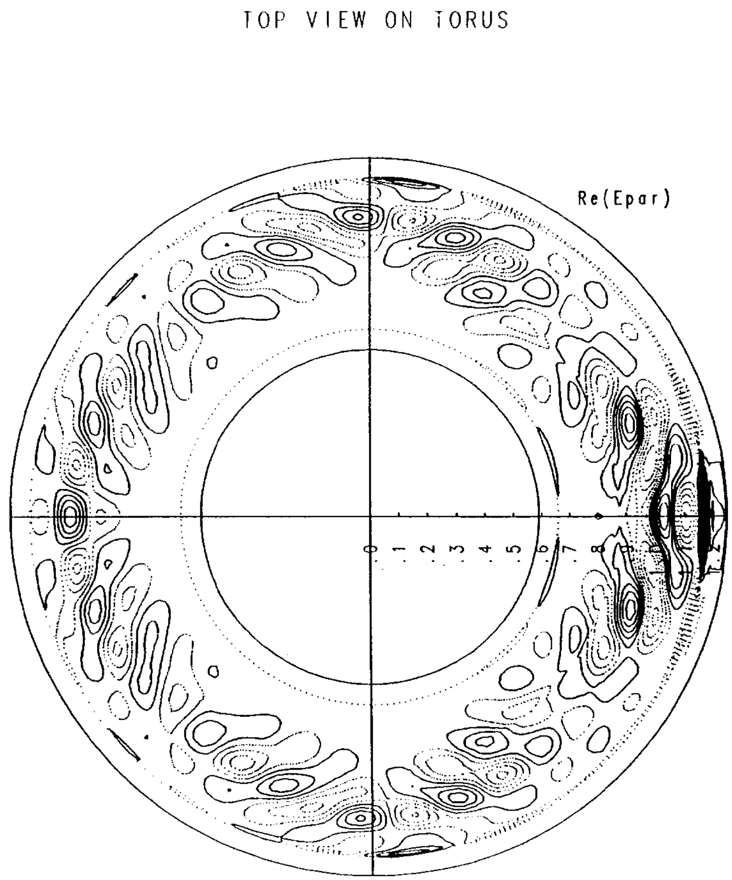

FIG. 9.—Top view on the torus. Re $(E_{\parallel})$ distribution.

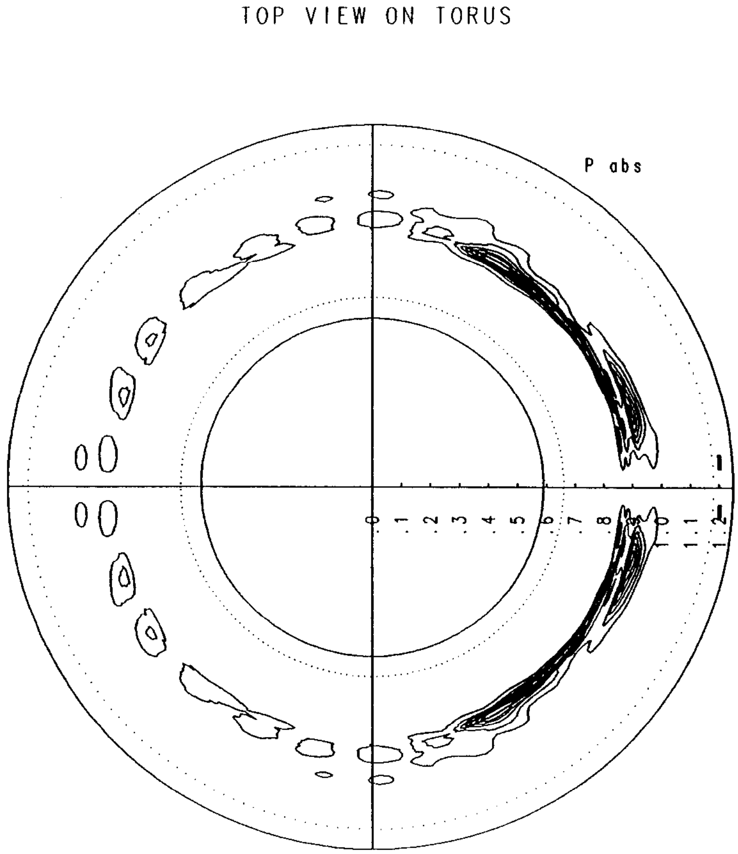

FIG. 10.—Top view on the torus. Contours of total absorbed power.

for a realistic Tokamak configuration showed better toroidal penetration of the $E_{\|}$ component in comparison with the other fast wave components. This can be understood by taking into account that $E_{\|}$ is larger for waves with high $k_{\|}$ but these waves do not contribute significantly to the total absorbed power and antenna loading resistance. As a conclusion we would like to mention that the whole ansatz (20) should be used in numerical calculations because condition (12) can be unfulfilled even in the hot central plasma. Calculations for the larger Tokamaks Alcator C-Mod and TFTR show similar behaviour and indicate the importance of properly considering the $E_{\|}$ and electron absorption terms.

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