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**ELECTRON CYCLOTRON HEATING AT DOWN-SHIFTED FREQUENCIES
IN EXISTING TOKAMAK DEVICES**

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Abstract

Plasma heating in existing tokamak devices by electron cyclotron waves with frequency (f) significantly smaller than the electron gyrofrequency (f_c) is investigated for the case of Maxwellian plasmas. It is shown that for central electron temperatures larger than 3 keV, strong absorption of extraordinary waves can occur at values of toroidal field for which the condition $f = f_c$ is not satisfied in the plasma region. The cases of $f = 60$ GHz and $f = 100$ GHz are discussed for the PLT and TFTR devices as representative of medium (≈ 30 kG) and high (≈ 50 kG) magnetic field tokamaks, respectively. Numerical calculations with a ray tracing code indicate that most of the rf energy is absorbed in a central plasma region.

These results are of practical interest because they significantly simplify the main technical problem of ECH in a tokamak reactor, i.e., the development of high frequency and high power microwave sources.

I. Introduction

Recent high power Electron Cyclotron Heating (ECH) experiments in *T-10* [1] and *Doublet-III* [2] have demonstrated the potential use of this form of plasma heating in a tokamak fusion reactor. Unfortunately, the type of ECH that has been so far considered applicable to a reactor, i.e., launching of ordinary waves from the low field side, has some serious drawbacks. In fact, since the rf energy is deposited in a narrow plasma region where the electron cyclotron frequency (f_c) is about equal to the wave frequency (f), this type of ECH requires the use of high frequency microwave sources. For an INTOR-type tokamak, with a toroidal magnetic field of 55 kG, the required wave frequency is about 150 GHz. Furthermore, since the ordinary mode is strongly affected by refraction when the electron plasma frequency (f_p) approaches the value of f , this type of ECH has also a very restrictive density limit.

Although progress in the development of high frequency and high power microwave sources is expected to occur in the near future, it is of great interest to explore alternative ways in which the technological difficulties are minimized. One has been recently discussed in *Refs.* [3-5], where the absorption by a Maxwellian plasma of waves with the extraordinary mode and a frequency significantly smaller than the central electron gyrofrequency has been investigated.

The basic idea can be stated as follows: in a sufficiently hot and dense Maxwellian plasma, the number of energetic electrons is sufficient for a strong absorption of extraordinary electron cyclotron waves at down-shifted frequencies, i.e., with $f < f_c$. So, instead of considering ECH as a heating system for start-up, we assume it is applied to a preheated plasma. Fortunately, as we shall prove in this paper, in large devices like TFTR or JET the plasma conditions necessary for this new type of ECH are obtained with ohmic heating.

For the absorption of electron cyclotron waves at large frequency down-shift, i.e., when the component $N_{||}$ of the wave index along the magnetic field satisfies the condition $N_{||}^2 < (f_c^2/f^2 - 1)$, the relativistic theory of wave absorption must be used. The role of the relativistic mass variation on wave damping has been extensively investigated in *Ref.* [6], where it has been shown that the condition $N_{||}^2 \gg T_e/mc^2$ is not sufficient to guarantee the validity of the nonrelativistic approximation. This is easily seen by considering the nonrelativistic and the relativistic resonance equations which, for $N_{||} > 0$, are

$$\frac{p_{||}}{mc} = \frac{1 - f_c/f}{N_{||}}, \quad (1)$$

and

$$\frac{p_{||}}{mc} = \frac{N_{||} f_c/f - (N_{||}^2 - 1 + f_c^2/f^2)^{1/2}}{1 - N_{||}^2}, \quad (2)$$

respectively, where $p_{||}$ is the momentum component parallel to the magnetic field $\vec{B}$, c is the speed of light, and m is the electron rest mass. Equation (2) is valid for $p_{||}^2 \gg p_{\perp}^2$, with $p_{\perp}$ the momentum component perpendicular to $\vec{B}$. Note that for $N_{||}^2 \gg |1 - f_c^2/f^2|$

Eq.(2) coincides with Eq.(1). For given values of f_c/f and $N_{||}$, the value of $p_{||}$ obtained from Eq.(1) is greater than that obtained from Eq.(2). This is shown in Fig.1 where the kinetic energy of electrons that satisfies the relativistic (E_r) and the nonrelativistic (E_{nr}) resonance condition are shown as a function of $N_{||}$ for $f_c/f = 1.2$. The ratio of the relativistic to the nonrelativistic wave dampings is approximately given by the ratio of these two electronic populations. In a Maxwellian plasma it is equal to $\exp[(E_{nr} - E_r)/T_e]$, which, as shown in Fig.1 for $T_e = 2 \text{ keV}$, can be much larger than unity for $N_{||}^2 \gg T_e/mc^2$. Nevertheless, this condition is often erroneously quoted as the range of validity of the nonrelativistic theory.

One feature of electron cyclotron wave absorption that makes the ECH discussed in this paper feasible, is that the monotonic decrease for increasing values of density of the e-mode damping at $f \approx f_c$ no longer holds for $f \ll f_c$ [3,4]. On the contrary, the damping at down-shifted frequencies increases with n_e , at moderate electron densities, and varies like n_e^{-1} at high densities.

At present, high power and long pulse microwave sources are available in the frequency range of $\approx 60 \text{ GHz}$ [1] and $\approx 83 \text{ GHz}$ [2]. In this paper we want to show that these sources can be used for ECH at down-shifted frequency in existing tokamaks with toroidal fields of $30 - 40 \text{ kG}$. As an example, in Sec.II we discuss heating of a PLT-type tokamak with 60 GHz waves at $\approx 30 \text{ kG}$.

Higher frequency microwave sources are under development. In Sec.III we consider the use of 100 GHz sources, a small extrapolation of the existing ones, for heating a TFTR-type tokamak at 50 kG . In both sections we present numerical results obtained with a ray tracing code and the relativistic dispersion relation. For completeness, a brief account of the wave damping is presented in the Appendix.

II. ECH in PLT with 60 GHz waves

We first consider the absorption of extraordinary waves with a frequency of 60 GHz in PLT. In this device the plasma torus has minor radius $a = 40 \text{ cm}$, major radius $R = 132 \text{ cm}$, and toroidal field $B = 30 \text{ kG}$ ($f_c = 84 \text{ GHz}$).

In the usual toroidal coordinates (r, θ, ϕ) , where r is the minor radius, θ is the poloidal angle, and ϕ is the toroidal angle, we assume (with standard notation) the following plasma profiles: $n_e(r) = n_e(0)(1 - (r/a)^2)$, $T_e(r) = T_e(0)(1 - (r/a)^2)^{3/2}$, $B_\phi(r) = B/(1 + r \cos(\theta)/R)$, $B_\theta(r) = rB_\phi/Rq(r)$, and $q(r) = q_0 + (q_a - q_0)(r/a)^2$. In the following we shall assume $q_0 = 1$ and $q_a = 3$. The launching conditions are defined by the poloidal coordinate (θ_a) of the antenna (for which we shall always assume $r = a$), and by the two components of the wave refractive index vector, $N_\phi = \sin(\alpha)$ and $N_\theta = \sin(\beta)$. Given a set of initial conditions, the wave path and absorption are calculated with a ray tracing code which is briefly described in the Appendix.

In Ref.[3] the wave was launched from the equatorial plane. For PLT we shall, instead, consider an antenna on the top (or bottom) of the torus, i.e., with $\theta_a = 90^\circ$ (or $\theta_a = -90^\circ$). For the plasma parameters of PLT, this type of wave launching produces better power deposition profiles (i.e., more central) than the launching of Ref.[3]. Moreover, it allows

the use of low initial electron temperature plasmas when the $f = f_c$ layer is slightly inside the plasma.

The poloidal projection of three ray paths with $\theta_a = 90^\circ$, $\alpha = 60^\circ$, $\beta = 0^\circ$, $B = 28.5$ kG, and different values of plasma density, are shown in Fig.2. The power deposition profiles, $\eta(r)$, are shown in Fig.3 for $T_e(0) = 3$ keV. The function $\eta(x)$ is defined as the fraction of rf power which is absorbed in the region $0 \leq r \leq x$. In all three cases we obtain good deposition profiles, i.e., with $\eta(a/2) > 1/2$. In the case of $n_e(0) = 5 \times 10^{13} \text{ cm}^{-3}$ the wave is almost completely absorbed.

It appears from Fig.3 that the value of the total absorbed power increases with the plasma density. This is due to an increased bending of the ray path toward the low field side which brings the wave closer to the $f = f_c$ condition.

The wave damping is a strong function of the magnetic field. For instance, if the magnetic field $B = 28$ kG, the wave absorption is complete in all three cases. It is also a strong function of α and $T_e(0)$, as shown in Fig.4, where we plot the value of $\eta(a)$ as a function of α for three values of $T_e(0)$.

As the electron temperature increases, it is possible to use larger values of magnetic field. For instance, with the same launching geometry of Fig.2 we obtain $\eta(a) = 0.9$ with $T_e(0) = 5$ keV, $n_e(0) = 5 \times 10^{13} \text{ cm}^{-3}$, and $B = 30$ kG. Alternately, we can decrease the value of α and obtain good deposition profiles at larger plasma densities. We obtain $\eta(a) = 1.0$ with $\alpha = 35^\circ$, $n_e(0) = 7 \times 10^{13} \text{ cm}^{-3}$, $T_e(0) = 5$ keV, and $B = 28$ kG.

As mentioned above, it is possible to obtain good power deposition profiles at low initial electron temperatures in PLT by bringing the resonance layer $f = f_c$ slightly inside the plasma torus. This is demonstrated in Fig.5, where $\eta(r)$ is shown for $T_e(0) = 1.5$ keV, $n_e(0) = 5 \times 10^{13} \text{ cm}^{-3}$, $B = 26$ kG, $\alpha = 50^\circ$, and $\beta = 0^\circ$.

III. ECH in TFTR with 100 GHz waves

In this section we present numerical results on the absorption of extraordinary waves with a frequency of 100 GHz in TFTR. The plasma torus of this device has minor radius 80 cm, major radius 250 cm, and toroidal field 50 kG ($f_c = 140$ GHz).

We assume the same type of plasma profiles used in Sec.II, and we first consider three cases similar to those of Fig.3, with the same launching geometry ($\theta = 90^\circ$, $\alpha = 60^\circ$, $\beta = 0^\circ$) and temperature (3 keV), but with three different values of plasma density and $B = 47.5$ kG. With these plasma parameters the ratios f_c/f and f_p/f are the same in the two devices. The calculated power deposition profiles (Fig.6) show that the wave damping is stronger in TFTR than in PLT. This is due to the larger dimensions of TFTR and the higher wave frequency. The same phenomenon is shown by Fig.7, where we plot $\eta(a)$ versus the angle α for the values of $T_e(0)$ of Fig.4.

Other types of geometries can be used for launching the wave. The one used in Ref.[3] has the advantage of a good machine accessibility but it tends to produce deposition profiles which are more shifted toward the plasma edge than those obtained with a top launcher. A good compromise is shown in Fig.8 where the wave is launched from $\theta_a = 45^\circ$. This type of launching, like the equatorial one, has also the advantage that at high densities the wave

path crosses twice the absorption region. The result is that we can obtain strong wave damping in TFTR even at low electron temperature, as shown in *Fig.9* for $T_e(0) = 2 \text{ keV}$. Note that this range of temperatures has been obtained in TFTR with only ohmic heating.

Figure 9 shows also the wave damping in a case of high electron temperature (8 keV), where complete absorption is achieved at larger values of density ($2 \times 10^{14} \text{ cm}^{-3}$) and magnetic field (50 kG). At high temperatures it is possible to obtain strong wave absorption at larger values of toroidal field. This is illustrated in *Fig.10*, where the value of B needed for obtaining $\eta(a) = 0.95$ is shown as a function of $T_e(0)$ when $n_e(0) = 1.4 \times 10^{14} \text{ cm}^{-3}$, $\theta_a = 50^\circ$, $\alpha = 50^\circ$, and $\beta = 0^\circ$. It appears that in the thermonuclear range of temperatures ($T_e(0) \approx 30 \text{ keV}$) the toroidal magnetic field can be increased to 80 kG . The wave absorption can be further optimized with a broader electron temperature profile. For instance, we obtain the same wave absorption of *Fig.10* with $B = 80 \text{ kG}$, $\alpha = 60^\circ$ and a parabolic temperature profile with $T_e(0) = 25 \text{ keV}$.

IV. Conclusion

In conclusion, we have shown that ECH at down-shifted frequencies can be tested in present day tokamaks with the existing microwave sources (60 GHz) or with those under development (100 GHz). Our numerical results indicate that Maxwellian plasmas, in the range of electron temperature which has been already achieved in both PLT and TFTR, strongly absorb electron cyclotron waves at values of magnetic fields for which the condition $f = f_c$ is not satisfied inside the plasma region. In the case of 100 GHz , we find that at thermonuclear temperatures the toroidal magnetic field of a plasma torus with the dimensions of TFTR can be increased to 80 kG .

These results, if experimentally confirmed, are of great practical importance because they significantly simplify the solution of the main technical problem of ECH in a fusion reactor, i.e., the construction of high frequency and high power microwave sources.

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Appendix : Wave Path and Absorption

The wave trajectory is obtained by solving the ray equations

$$\frac{d\vec{r}}{ds} = -\frac{\partial D / \partial \vec{k}}{|\partial D / \partial \vec{k}|} ,$$

$$\frac{d\vec{k}}{ds} = \frac{\partial D / \partial \vec{r}}{|\partial D / \partial \vec{k}|} ,$$

in the cold plasma approximation, and the wave absorption is obtained from the hot plasma dispersion relation [6]

$$\begin{aligned} D = & N_{\perp}^4 [\epsilon_{11}(1 - \chi_{33}) + \chi_{13}(\chi_{13} + 2N_{\parallel}) + N_{\parallel}^2 \chi_{33}] - N_{\perp}^2 \left[\epsilon_{12}^2 (1 - \chi_{33}) + (\epsilon_{11} - N_{\parallel}^2) \right. \\ & \left. [(\epsilon_{11} - N_{\parallel}^2)(1 - \chi_{33}) + \epsilon_{33}^2 + \chi_{13}^2 + (N_{\parallel} + \chi_{13})^2] - 2i\epsilon_{12}\chi_{13}(N_{\parallel} + \chi_{13}) \right] \\ & + \epsilon_{33}^2 [(\epsilon_{11} - N_{\parallel}^2)^2 + \epsilon_{12}^2] = 0 \end{aligned}$$

where $\vec{r}$ is the spatial coordinate, s is the arc length along the ray, $\vec{k}$ is the wave vector, ω is the wave frequency, $N_{\parallel}$ and $N_{\perp}$ are the components of the refractive index vector $\vec{N} = (c/\omega)\vec{k}$ parallel and perpendicular to $\vec{B}$, $\chi_{13} = \epsilon_{13}/N_{\perp}$, $\chi_{33} = (\epsilon_{33} - \epsilon_{33}^0)/N_{\perp}^2$, ϵ_{ij} are the components of the hot plasma dielectric tensor, and $\epsilon_{33}^0 = 1 - \omega_p^2/\omega^2$. For a Maxwellian plasma, at the lowest relevant order in the Larmor radius, $\epsilon_{ij} = \epsilon'_{ij} + i\epsilon''_{ij}$, where

$$\begin{aligned} \epsilon'_{11} &= 1 - \frac{\omega_p^2/2\omega^2}{1 + \omega_c/\omega} - \frac{\omega^2}{2\omega^2} \mu \left[1 + \int_{-\infty}^{+\infty} du \Lambda(u) \right] , \\ \epsilon'_{12} &= -i \frac{\omega_p^2/2\omega^2}{1 + \omega_c/\omega} + i \frac{\omega^2}{2\omega^2} \mu \left[1 + \int_{-\infty}^{+\infty} du \Lambda(u) \right] , \\ \epsilon'_{13} &= -\frac{\omega_p^2}{2\omega\omega_c} N_{\perp} \mu \int_{-\infty}^{+\infty} du \Lambda(u) , \\ \epsilon'_{33} &= \epsilon_{33}^0 - \frac{\omega^2}{2\omega_c^2} N_{\perp}^2 \left[1 + \mu \int_{-\infty}^{+\infty} du u^2 \Lambda(u) \right] , \\ \Lambda(u) &= [d/(2\pi)^{1/2}] \mu^{3/2} E_i(-\mu d) \exp(\mu d - \mu u^2/2) , \\ d &= 1 - \omega_c/\omega - N_{\parallel} u + u^2/2, \quad \mu = mc^2/T_e , \end{aligned}$$

and $E_i(x)$ is the exponential integral.

The anti-Hermitian part of ϵ_{ij} is given by

$$\begin{aligned}
\epsilon''_{11} &= (\pi\omega_p^2/2\omega^2)(R/N_{\parallel})^{3/2}[\mu S/(1-N_{\parallel}^2)^{1/2}I_{3/2}(\xi)\exp[\mu(1-\frac{\omega_c/\omega}{1-N_{\parallel}^2})]] , \\
\epsilon''_{12} &= -i\epsilon''_{11} , \\
\epsilon''_{13} &= (\pi\omega_p^2/2\omega\omega_c)(R^{5/2}/N_{\parallel}^{3/2})[N_{\perp}\mu S/(1-N_{\parallel}^2)^{3/2}] \\
&\quad [N_{\parallel}(\omega_c/\omega)I_{3/2}(\xi)/R - I_{5/2}(\xi)]\exp[\mu(1-\frac{\omega_c/\omega}{1-N_{\parallel}^2})] , \\
\epsilon''_{33} &= (\pi\omega_p^2/2\omega_c^2)(R^{7/2}/N_{\parallel}^{3/2})[N_{\perp}^2\mu S/(1-N_{\parallel}^2)^{5/2}] \\
&\quad [I_{3/2}(\xi)(1+\frac{N_{\parallel}^2\omega_c^2}{R^2\omega^2}) - 2I_{5/2}(\xi)(\frac{2}{\xi} + \frac{N_{\parallel}\omega_c}{R\omega})]\exp[\mu(1-\frac{\omega_c/\omega}{1-N_{\parallel}^2})] , \\
R &= (\omega_c^2/\omega^2 - 1 + N_{\parallel}^2)^{1/2}, \quad S = \frac{1}{2}(1 + \frac{N_{\parallel}^2 - 1 + \omega_c^2/\omega^2}{|R|^2}) , \\
\xi &= N_{\parallel}R\mu/(1-N_{\parallel}^2) .
\end{aligned}$$

The real part of $N_{\perp}$ is well approximated by the cold plasma limit, i.e.,

$$\begin{aligned}
\text{Re } N_{\perp}^2 &= 1 - N_{\parallel}^2 - \frac{\omega_p^2}{\omega^2} \\
&\quad + \left(\frac{\omega_p^2\omega_c}{2\omega^3}\right) \frac{\pm[(1-N_{\parallel}^2)^2(\omega_c^2/\omega^2) + 4N_{\parallel}^2(1-\omega_p^2/\omega^2)]^{1/2} - (1-N_{\parallel}^2)(\omega_c/\omega)}{1 - (\omega_p^2/\omega^2) - (\omega_c^2/\omega^3)} ,
\end{aligned}$$

where the upper (lower) sign refers to the o(e)-mode. From this equation one obtains, that in order to couple the e-mode to the plasma from the low-B side of the torus, the wave frequency must fulfill the condition $\omega_-(0) < \omega < \omega_+(a)$, where

$$\omega_{\pm}(x) = \frac{\omega_c(x)}{2} \left[\left(1 + \frac{4\omega_p^2/\omega_c^2(x)}{1-N_{\parallel}^2} \right)^{1/2} \pm 1 \right] ,$$

for $N_{\parallel}^2 \leq (1 + 2\omega/\omega_c)^{-1}$, and $\omega < \omega_+(a)$ for $N_{\parallel}^2 > (1 + 2\omega/\omega_c)^{-1}$. For propagation from the high-B side the condition is $\omega_-(0) < \omega < (\omega_p^2 + \omega_c^2)^{1/2}$.

The fraction of rf power, $p(s)$, absorbed by the plasma is given by

$$p(s) = 1 - \exp[-2 \int_0^s \text{Im } \vec{k} \cdot \frac{d\vec{r}}{ds} ds] ,$$

where the integral is along the ray path.

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Figure Captions

- Fig. 1* Energy of electrons that satisfy the relativistic (E_r) and the nonrelativistic (E_{nr}) resonance equation, for $f_c/f = 1.2$. The dotted line is the ratio of these two electronic populations in a Maxwellian plasma with $T_e = 2$ keV.
- Fig. 2* Poloidal projection of ray paths in PLT with $f = 60$ GHz, $\theta_a = 90^\circ$, $\alpha = 60^\circ$, $\beta = 0^\circ$, $B = 28.5$ kG, and : (a) $n_e(0) = 3 \times 10^{13} \text{ cm}^{-3}$, (b) $n_e(0) = 4 \times 10^{13} \text{ cm}^{-3}$, (c) $n_e(0) = 5 \times 10^{13} \text{ cm}^{-3}$.
- Fig. 3* Power deposition profiles for the cases of *Fig. 2* with $T_e(0) = 3$ keV.
- Fig. 4* Fraction of power absorbed in PLT vs. α for $n_e(0) = 5 \times 10^{13} \text{ cm}^{-3}$, and $T_e(0) = 3, 4$, and 5 keV. Other conditions are those of *Fig. 2*.
- Fig. 5* Power deposition profiles in PLT with $T_e(0) = 1.5$ keV, $n_e(0) = 5 \times 10^{13} \text{ cm}^{-3}$, $B = 26$ kG, $f = 60$ GHz, $\theta_a = 90^\circ$, $\alpha = 50^\circ$, $\beta = 0^\circ$.
- Fig. 6* Power deposition profiles in TFTR with $f = 100$ GHz, $B = 47.5$ kG, and: (a) $n_e(0) = 8.3 \times 10^{13} \text{ cm}^{-3}$, (b) $n_e(0) = 1.1 \times 10^{14} \text{ cm}^{-3}$, (c) $n_e(0) = 1.4 \times 10^{14} \text{ cm}^{-3}$. Other conditions are those of *Fig. 3*.
- Fig. 7* Fraction of power absorbed in TFTR vs. α for $n_e(0) = 1.4 \times 10^{14} \text{ cm}^{-3}$, and $T_e(0) = 3, 4$, and 5 keV. Other conditions are those of *Fig. 6*.
- Fig. 8* Poloidal projection of ray paths in TFTR with $f = 100$ GHz, $B = 50$ kG, $n_e(0) = 2 \times 10^{14} \text{ cm}^{-3}$, $\theta_a = 50^\circ$, $\alpha = 30^\circ$, $\beta = 0^\circ$ (dotted line), and $\beta = -5^\circ$ (full line).
- Fig. 9* Power deposition profiles in TFTR with $f = 100$ GHz, $\beta = 0^\circ$, and:
 (a) $\theta_a = 40^\circ$, $\alpha = 50^\circ$, $B = 47$ kG, $T_e(0) = 2$ keV, $n_e(0) = 1.4 \times 10^{14} \text{ cm}^{-3}$,
 (b) $\theta_a = 50^\circ$, $\alpha = 30^\circ$, $B = 50$ kG, $T_e(0) = 8$ keV, $n_e(0) = 2 \times 10^{14} \text{ cm}^{-3}$.
- Fig. 10* Magnetic field needed for $\eta(a) = 0.95$ as a function of $T_e(0)$ when $n_e(0) = 1.4 \times 10^{14} \text{ cm}^{-3}$, $f = 100$ GHz, $\theta_a = 50^\circ$, $\alpha = 50^\circ$, and $\beta = 0^\circ$.

Fig. 1 Energy of electrons that satisfy the relativistic (E_r) and the nonrelativistic (E_{nr}) resonance equation, for $f_c/f = 1.2$. The dotted line is the ratio of these two electronic populations in a Maxwellian plasma with $T_e = 2$ keV.

Fig. 2 Poloidal projection of ray paths in PLT with $f = 60$ GHz, $\theta_a = 90^\circ$, $\alpha = 60^\circ$, $\beta = 0^\circ$, $B = 28.5$ kG, and : (a) $n_e(0) = 3 \times 10^{13} \text{ cm}^{-3}$, (b) $n_e(0) = 4 \times 10^{13} \text{ cm}^{-3}$, (c) $n_e(0) = 5 \times 10^{13} \text{ cm}^{-3}$.

Fig. 3 Power deposition profiles for the cases of Fig.2 with $T_e(0) = 3 \text{ keV}$.

Fig. 4 Fraction of power absorbed in PLT vs. α for $n_e(0) = 5 \times 10^{13} \text{ cm}^{-3}$, and $T_e(0) = 3, 4$, and 5 keV . Other conditions are those of Fig. 2.

Fig. 5 Power deposition profiles in PLT with $T_e(0) = 1.5$ keV, $n_e(0) = 5 \times 10^{13} \text{ cm}^{-3}$,
 $B = 26$ kG, $f = 60$ GHz, $\theta_a = 90^\circ$, $\alpha = 50^\circ$, $\beta = 0^\circ$.

Fig. 6 Power deposition profiles in TFTR with $f = 100 \text{ GHz}$, $B = 47.5 \text{ kG}$, and: (a) $n_e(0) = 8.3 \times 10^{13} \text{ cm}^{-3}$, (b) $n_e(0) = 1.1 \times 10^{14} \text{ cm}^{-3}$, (c) $n_e(0) = 1.4 \times 10^{14} \text{ cm}^{-3}$. Other conditions are those of Fig. 3.

Fig. 7 Fraction of power absorbed in TFTR vs. α for $n_e(0) = 1.4 \times 10^{14} \text{ cm}^{-3}$, and $T_e(0) = 3, 4, \text{ and } 5 \text{ keV}$. Other conditions are those of Fig. 6.

Fig. 8 Poloidal projection of ray paths in TFTR with $f = 100$ GHz, $B = 50$ kG, $n_e(0) = 2 \times 10^{14} \text{ cm}^{-3}$, $\theta_a = 50^\circ$, $\alpha = 30^\circ$, $\beta = 0^\circ$ (dotted line), and $\beta = -5^\circ$ (full line).

Fig. 9 Power deposition profiles in TFTR with $f = 100$ GHz, $\beta = 0^\circ$, and:
 (a) $\theta_a = 40^\circ$, $\alpha = 50^\circ$, $B = 47$ kG $T_e(0) = 2$ keV, $n_e(0) = 1.4 \times 10^{14} \text{ cm}^{-3}$,
 (b) $\theta_a = 50^\circ$, $\alpha = 30^\circ$, $B = 50$ kG $T_e(0) = 8$ keV, $n_e(0) = 2 \times 10^{14} \text{ cm}^{-3}$.

Fig.10 Magnetic field needed for $\eta(a) = 0.95$ as a function of $T_e(0)$ when $n_e(0) = 1.4 \times 10^{14} \text{ cm}^{-3}$, $f = 100 \text{ GHz}$, $\theta_a = 50^\circ$, $\alpha = 50^\circ$, and $\beta = 0^\circ$.

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