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TWO-ION ICRF HEATING IN TOKAMAKS

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ABSTRACT

The practical consequences for tokamak plasma heating in the ion cyclotron frequency regime of the two-dimensional treatment of the two-ion mode conversion layer are analyzed. The problem of evaluation of the condition for fast wave resonance is analyzed, as well as the limitations imposed by warm plasma effects. Simple ways to find the mode conversion surfaces when they exist are presented. Also for large tokamaks, it is possible to obtain mode conversion conditions for realistic antenna spectra provided species concentration and frequency are chosen such that the surface $\varepsilon_{\perp}=0$ intersects the plasma midplane just outside of the magnetic axis.

1. Introduction

One of the ICRF heating scenarios that has been successfully tested on tokamaks is the so called two-ion "mode conversion" or "wave conversion" scheme, where a local "resonance" (near the cold plasma two-ion hybrid resonance of the slow wave) of the fast magnetosonic wave couples the wave energy to a slow wave. Hellsten and Tennfors has earlier shown [1,2] that these mode conversion layers cannot cross the magnetic surfaces as is assumed in the "traditional" treatment [3,4], where the parallel wave number is assumed to be approximately constant and given by the antenna spectrum. This distinction is not always essential; both types of surfaces are present in the plasma under similar conditions and both have to be located in regions where $\varepsilon_{\perp}$ is small, otherwise the fast wave resonance is too much damped by thermal effects and the wave conversion does not occur. However the differences are considerable and a judgement on the applicability of this scheme or an estimate of the power deposition profile should not be based on the one-dimensional picture, even if that simplifies the evaluation. The condition for fast wave resonance (in the m_e=0 limit) is an ordinary differential equation along a poloidal intersection of the magnetic surface instead of the algebraic equation obtained in the one-dimensional case. Simplified evaluations of this criterion where given in Refs. [5,6]and further discussed in Ref.[7]. The aim of the present work is to analyze the problem of evaluation of the resonance condition and to derive simplified criteria that are more readily applicable to actual experiments.

For a given plasma equilibrium, the condition for fast wave resonance defines a set of resonance frequencies for each magnetic surface. Unfortunately, the position of the cyclotron resonances varies with frequency, which makes the evaluation complicated. If instead the frequency is fixed in relation to the equilibrium magnetic field, the condition can be expressed in terms of resonance ion densities for each magnetic surface. The so obtained resonance density profiles can then be compared to the equilibrium density profile in order to find the resonance surfaces. This approach also has the advantage that it simulates heating situations, where the frequency is in general fixed and determined by the generator.

2. The resonance condition

Using the coordinate system (ψ,ζ,θ) with "straight" field lines given in Ref.[1], the differential equation determining the fast wave resonances reads

$$(\frac{B}{B_P})^2 D(\frac{B_P}{B})^2 DE_{0\psi} + (\frac{qRB\omega}{B_T c})^2 \varepsilon_\perp E_{0\psi} = 0 \qquad (1)$$

where $E_{0\psi}$ is the leading order term of the singular electric field, ψ is the magnetic flux coordinate, ζ is a poloidal coordinate, and θ is the toroidal angle,

$$D = \partial/\partial\zeta + inq,$$

$$q = (1/2\pi) \oint d\ell B_T/RB_P,$$

n is the toroidal mode number, and where B, B_T and B_P denote the total, toroidal and poloidal magnetic field strengths, respectively.

The perpendicular component of the dielectric tensor, $\varepsilon_\perp$, for a cold plasma reads

$$\varepsilon_\perp = 1 + \sum_\alpha(\omega_{p\alpha}/(\omega_{c\alpha}^2 - \omega^2)),$$

and may vary strongly along a magnetic surface, especially for surfaces intersecting a fundamental ion cyclotron resonance surface and/or an $\varepsilon_\perp$=0 surface.

By expressing the leading order electric field as

$$E_{0\psi} = F(\zeta)\exp(-inq\zeta)$$

where $F(\zeta)$ acts as an amplitude modulation of a travelling wave, we obtain

$$F'' + f(\zeta)F = 0 \qquad (2)$$

where

$$f(\zeta) = (\frac{qRB\omega}{B_T c})^2 \varepsilon_\perp(\zeta).$$

Eq.(2) must be satisfied on the surface with adequate boundary and periodicity conditions applied. Since $E_{0\psi}$ is single-valued on the surface, and exp(-inqζ) is single-valued on surfaces where nq is an integer, F can be single-valued only on surfaces where q is rational. On other magnetic surfaces, this factorisation of $E_{0\psi}$ is inadequate. We expect, however, the resonance condition to vary continuously with the flux coordinate and may therefore restrict the evaluation to surfaces where nq meets this requirement. We also note, that F may change sign when is changed by 2π, provided that exp(-inqζ) changes sign simultaneously, which is the case if 2nq is an odd integer. The periodicity condition for F becomes

$$F(\zeta+2\pi) = \pm F(\zeta) \qquad (3)$$

where the upper sign is taken when 2nq is even and the lower when 2nq is odd.

The character of the amplitude function F(ζ) determines the deposition of power along the surface; the locally absorbed power is proportional to F^2. Fig.1 illustrates the different classes of magnetic surfaces in a two ion species tokamak plasma, which we will discuss separately below. Since the character of the problem is insensitive to the detailed equilibrium, we will here use a simplified geometry with circular magnetic surfaces. In Fig.1a, two ion cyclotron resonances are present in the plasma; one on each side of the magnetic axis. The surfaces $\varepsilon_\perp=0$ and $\varepsilon_\perp=(cn/\omega R)^2$ are also indicated, the former tending to the innermost cyclotron resonance at the boundary, where the density is low, due to the term "1" in $\varepsilon_\perp$, while the latter tends to the outer cyclotron resonance due to the term $(cn/\omega R)^2$. For low concentration of the ion species with the smallest Ze/m, these surfaces pass on the inside of the magnetic axis (Fig.1a), and reversely when the other ion is in minority (Fig.1b). The shape of F(ζ) depends on the behaviour of $\varepsilon_\perp$ along the surface and we may distinguish between surfaces with $\varepsilon_\perp>0$ everywhere, and surfaces where changes sign due to intersections with an $\varepsilon_\perp=0$ surface and/or an ion cyclotron resonance surface.

3. Magnetic surfaces intersecting $\varepsilon_\perp=0$

In a tokamak the $\varepsilon_\perp=0$ surface is nearly vertical (Fig.1). On magnetic surfaces crossing this surface, WKB-solutions to Eq.(2) can at most be used to some distance from it. Close to the surface a linear approximation $\varepsilon_\perp \propto \zeta$ turns Eq.(2) into an Airy equation:

$$F'' + f'(0)\zeta F = 0 \qquad (4)$$

Of the two solutions, $Ai(-f'(0)^{1/3}\zeta)$ and $Bi(-f'(0)^{1/3}\zeta)$, the latter has to be small for $\varepsilon_\perp>0$ since it grows exponentially for negative $\varepsilon_\perp$. For large arguments the asymptotic form of $Ai(-f'(0)^{1/3}\zeta)$ reads

$$Ai(-f'(0)^{1/3}\zeta) = \frac{1}{\sqrt{\pi}} \quad (f'(0)^{1/3}\zeta)^{-1/4} \sin(\sqrt{f'(0)}\zeta + \pi/4) =$$

$$= \frac{1}{\sqrt{\pi}} \quad (f'(0)^{1/3}\zeta)^{-1/4} \sin(\int_0^\zeta \sqrt{f}\, d\zeta + \pi/4)$$

At some distance from $\varepsilon_\perp=0$, $F(\zeta)$ deviates from the Airy function but still oscillates as long as $\varepsilon_\perp$ is positive. Thus, for magnetic surfaces intersecting the $\varepsilon_\perp=0$ surface, but not the outer ion cyclotron resonance, matching to an Ai-function at both ends and observing symmetry or anti-symmetry about the midplane, yields the condition for fast wave resonance. Close to the midplane intersection, $\varepsilon_\perp$ is nearly constant, and a WKB solution may be used. The form of $F(\zeta)$ suggested by the Airy function is

$$F(\zeta) \propto \sin(\int_0^\zeta \sqrt{f}\, d\zeta + \pi/4) \qquad (5)$$

from which we obtain

$$\int_0^{\zeta_m} \sqrt{f}\, d\zeta = \nu \frac{\pi}{2} - \frac{\pi}{4} \qquad (6)$$

where $\zeta_m \leqslant \pi$ is the value at the midplane of the plasma. It must be noted, that ν is not a poloidal mode number for the wave but only refers to the amplitude function $F(\zeta)$ and denotes the number of maxima in F^2 between the two $\epsilon_\perp=0$ intersections. We further note, that the toroidal mode number does not appear here as it did in the previous works [5-7], where the poloidal mode number was assumed to be small. From Eq.(6) resonance density profiles can be computed for each ν and the location of each surface determined from the ion density profile of the plasma.

In Fig.2, the quantity $(\rho B/B_p)^2 n_i$, where ρ is the minor radius of the magnetic surface and n is the total ion number density, is computed as a function of ρ/R for a circular plasma cross-section, for given ion species concentration and position of the ion cyclotron resonances (as in Fig.1a, but with the outer cyclotron resonance placed on the outside of the plasma). The result may then be applied to actual tokamaks by scaling with the appropriate profile of B/B_p. The result is in good agreement with power absorption plots obtained from a two-dimensional code applied to the TCA tokamak[8].

In Fig.2, Eq.(5) is evaluated all the way down to the magnetic axis, i.e. also for surfaces with $\epsilon_\perp>0$, where it is no longer valid, the integration in those cases performed between the two midplane intersections. For surfaces with only a minor or no excursion into the $\epsilon_\perp<0$ area, the Airy equation is not an adequate approximation; parabolic cylinder functions would be more useful here. The criterion should gradually change to become (cf. section 4)

$$\int_0^\pi \sqrt{f}\, d\zeta = \begin{cases} \nu \frac{\pi}{2} \text{ for } 2nq+\nu \text{ even} \\ (\nu-1)\frac{\pi}{2} \text{ for } 2nq+\nu \text{ odd} \end{cases} \quad (7)$$

for surfaces entirely within the $\epsilon_\perp>0$ region, where $\epsilon_\perp$ varies only moderately. Consequently, curves of consecutive ν values approach each other in pairs near the magnetic axis.

However, the difference between conditions (5) and (6) is at most $\pi/4$ and does not alter the character of the profiles. The most striking feature is that the sharp increase in resonant density around the surface tangent to the $\epsilon_\perp=0$ surface. This localized increase implies that under rather general conditions one or more resonances appear close to this tangent surface, as was also noted in Ref.[6].

It is obvious that the location of the resonance surfaces is fully determined by the plasma equilibrium, the position of the cyclotron resonance surfaces and the $\varepsilon_\perp=0$ surface, and independent of the antenna spectrum. On the other hand, the coupling between each resonance surface and the antennae certainly depends on the antenna spectrum. We must also keep in mind, that the position of the surfaces where 2nq is an integer depends on the antenna spectrum.

For Tokamaks larger than TCA, higher values of ν are nessecary to match the plasma density profile and thus the neighbouring ν-modes come closer in space. The antenna spectrum will then determine which of these surfaces will actually absorb power, in a way similar to the approach used in Refs [5,6]. The increase in ν for large devices does not necessarily imply an unacceptably high value of $k_\parallel$, since ν represents merely a projection of the wave and the linear dimension along the magnetic field is also increased. High values ν of means a fine stucture which may be a disadvantage for the numerical code approach. However, the results of the present work would still be applicable to large devices. A concentration of resonances for different ν should be expected near the magnetic surface which is tangent to the $\varepsilon_\perp=0$ surface.

If the $\varepsilon_\perp=0$ surface is placed on the outside of the magnetic axis, as in Fig.1b, it is possible to meet the resonance condition for lower values of ν, since $\varepsilon_\perp$ remains moderate everywhere on the $\varepsilon_\perp>0$ section of the magnetic surface and since the linear dimension of the same sector is small for surfaces approaching $\varepsilon_\perp=0$.

We have here only discussed the parts of the magnetic surfaces that are located in the outermost $\varepsilon_\perp>0$ region. Some surfaces obviously intersect also the innermost cyclotron resonance. However, the behaviour of $F(\zeta)$ for $\varepsilon_\perp>0$ reduces the coupling between the two $\varepsilon_\perp>0$ regions and they can be treated separately.

4. Magnetic surfaces with $\varepsilon_\perp > 0$

In situations like in Fig.1a, where the $\varepsilon_\perp = 0$ surface intersects the midplane on the inside of the magnetic axis, a class of magnetic surfaces exists close to the magnetic axis with $\varepsilon_\perp > 0$ everywhere. On these surfaces $\varepsilon_\perp$ varies only moderately and a WKB solution is adequate. Here we choose to express $F(\zeta)$ as

$$F(\zeta) \propto \exp(i\int_0^\zeta \sqrt{f}\, d\zeta) \qquad (8)$$

with an arbitrary phase, in contrast to expression (5), which was matched to Ai functions. The poloidal mode number, m, for E_ψ may now be introduced through

$$m + nq = \begin{cases} \pm \frac{\nu}{2} \text{ for } 2nq+\nu \text{ even} \\ \pm \frac{\nu-1}{2} \text{ for } 2nq+\nu \text{ odd} \end{cases} \qquad (9)$$

In the previous section we gave condition (7) for surfaces where 2nq is an integer. We may now express the condition for fast wave resonance as

$$\int_0^\pi \sqrt{f}\, d\zeta = \pm\ (m+nq)\pi \qquad (10)$$

For small m, this condition for resonance near the magnetic axis coincides with the condition for the surface $\varepsilon_\perp = (cn/\omega R)^2$ to intersect the midplane near the magnetic axis.

For this class of surfaces, the similarity to the Alfvén wave resonance is obvious. As pointed out in Ref.[1], one perpendicular ion cyclotron resonance, which is the finite frequency generalization of the Alfvén wave resonance [9], appears for each ion species.

5. Surfaces with large $\varepsilon_\perp$

For magnetic surfaces passing through regions with large $\varepsilon_\perp$, the resonance condition (1) requires high values of the derivatives of $E_{0\psi}$ parallel to the magnetic field (corresponding to high $k_\parallel$ in a quasi-homogeneous plasma). In order to illustrate this situation, we introduce here a quasi-homogeneous model, where the wave can be described by a slowly varying $k_\parallel$, and where $\varepsilon_\perp$ varies in the direction along the magnetic field. In this case, the condition for fast wave resonance becomes the familiar

$$k_\parallel = \frac{\omega}{c}\sqrt{\varepsilon_\perp} \qquad (11)$$

For a warm plasma we have

$$\varepsilon_\perp = 1 + \sum_\alpha \frac{\omega_{p\alpha}^2}{2\omega\, k_\parallel v_{th\alpha}}\left(Z\left(\frac{\omega-\omega_{c\alpha}}{k_\parallel v_{th\alpha}}\right) + Z\left(\frac{\omega+\omega_\alpha}{k_\parallel v_{th\alpha}}\right)\right) \qquad (12)$$

where Z is the plasma dispersion functions [9]. For large arguments of Z, the cold plasma expression is recovered. Near a cyclotron resonance, one of the arguments $(\omega-\omega_{c\alpha})/k_\parallel v_{th\alpha}$ becomes small, and Z tends to $Z(C)=i\sqrt{\pi}$ as the resonance is approached. This term will then dominate, yielding as limiting value at the cyclotron resonance

$$\varepsilon_\perp \cong \frac{\omega_{p\alpha}^2}{2\; k_\parallel v_{th\alpha}}\, i\sqrt{\pi} \qquad (13)$$

Combination with the condition for fast wave resonance yields

$$k_{\parallel\,\omega=\omega_{c\alpha}} = \left(i\sqrt{\pi}\,\frac{\omega\omega_{p\alpha}^2}{2c^2 v_{th\alpha}}\right)^{1/3}$$

and

$$\varepsilon_{\perp\,\omega=\omega_{c\alpha}} = \left(i\sqrt{\pi}\,\frac{c\omega_{p\alpha}^2}{2c^2 v_{th\alpha}}\right)^{2/3}$$

which implies, that any oscillation of the wave function along the magnetic field is heavily damped. The damping causes a broadening of the mode conversion layer or, for large enough $\mathrm{Im}(k_{\parallel})$, elimination of the layer. The cyclotron damping is stronger than what could be expected from the one-dimensional treatment [3,4], where $k_{\parallel}$ is assumed to be equal to n/R and thus determined by the antenna structure.

A sequence of broadened resonance layers with the wave amplitude peaked near the $\varepsilon_{\perp}=0$ surface might result in a localized absorption in an approximately vertical band, similar to the surface where $\varepsilon_{\perp}=(cn/\omega R)^2$. It should be noted, however, that each surface in the sequence is aligned to a magnetic surface. The amplitude peak is caused by $\varepsilon_{\perp}$ being low and real. The location of the peak is not determined by n/R.

An attempt to evaluate the resonance condition for surfaces where the $\varepsilon_{\perp}>0$ section ended at an ion cyclotron resonance by using a simplified form of the plasma dispersion function was made in Ref.[5]. However, this approach is questionable in situations where $k_{\parallel}$ is not clearly defined. In an alternative approach, Cattanei [10,11] finds absorption by mode conversion only for magnetic surfaces not intersecting the ion cyclotron resonance. On the other hand, Villard's [8] computations show absorption layers also in cases where the surfaces were intersected by the ion cyclotron resonance. However this was done using an artificial damping term, and not with cyclotron damping.

For surfaces passing at a distance from the cyclotron resonance, with only a small imaginary part of $\varepsilon_{\perp}$, the plasma dispersion function may still be used to estimate warm plasma effects, like the relative importance of mode conversion heating and minority heating. Since, for low m, the resonance condition implies that the magnetic surface in question is intersected by the almost vertical surface defined by $\varepsilon_{\perp}=(cn/\omega R)^2$, the parallel wave number $k_{\parallel}$, if it can be defined, should be >n/R outside of this intersection. Thus thermal effects are expected to become larger than in the traditional picture, where $k_{\parallel}=n/R$, and experiments beleived to be run in the mode conversion regime may actually be in the minority heating regime.

Since $\mathrm{Im}(\varepsilon_{\perp})$ is small only when $\mathrm{Re}(\varepsilon_{\perp})$ is close to the cold plasma value, the latter is adequate for locating the mode conversion surfaces when they exist. It should also be noted, that the fast wave is not affected by the cyclotron resonance, on account of its polarization. The discussion of the influence of the warm plasma terms is based on the behaviour of the leading order term of the resonant electric field.

Consequently, in a broadened fast wave resonance region, the polarization of the wave is altered with enhanced cyclotron damping as a result.

The importance of the warm plasma terms depends strongly on the positions of the cyclotron resonance surfaces and the $\varepsilon_{\perp}=0$ surface, which can be adjusted in the experiments by varying the frequency and the relative concentration of species.

6. Conclusions

The shape of the mode conversion surfaces is significantly different from that usually presented [3,4]. Only when the mode conversion process is dominated by cyclotron damping, a structure similar to the traditional picture appears, with a sequence of surfaces where the amplitude is peaked near the $\varepsilon_\perp=0$ surface. Of course, for small n, these amplitude peaks are then also close to the surface $\varepsilon_\perp=(cn/\omega R)^2$, but this latter surface has no real physical significance, even if it has proved useful as a "rule-of-thumb" in a number of cases. This result has been confirmed by the works of Villard [8] and Cattanei [10,11]. In addition, the computations by Itoh et al. [12] show clearly that both power absorption and electric field pattern follows the poloidal magnetic field structure. These latter authors, however, fail to realize this; they only note that the absorption is peaked close to the surface $Re(\varepsilon_\perp)=(cn/\omega R)^2$.

The location of the surface $\varepsilon_\perp=0$ is the most important parameter for determining the location of the mode conversion surfaces. We may distinguish between three different regions:

i) If the $\varepsilon_\perp=0$ surface is far inside of the magnetic axis, most magnetic surfaces pass through regions where $\varepsilon_\perp$ is large, which implies a large amount of cyclotron damping.

ii) When this surface is closer to the magnetic axis, but still on the inside, some magnetic surfaces have $\varepsilon_\perp$ small enough to allow for mode conversion to appear. As pointed out in section 3, mode conversion is then likely to appear close to the magnetic surface which is tangent to the $\varepsilon_\perp=0$ surface. In Fig.2, fast wave resonances appear for surfaces all the way out to the boundary. However, cyclotron damping is expected to eliminate those who pass a region close to the outer ion cyclotron resonance, whith the possible exception of surfaces very close to the plasma boundary, where the temperature is low. Thus mode conversion is expected to occur near the surface tangent to the $\varepsilon_\perp=0$ surface and close to the plasma boundary.

iii) When the $\varepsilon_\perp=0$ surface intersect the midplane on the outside of the magnetic axis, the magnetic surfaces immediately outside of the one tangent to $\varepsilon_\perp=0$, have a short section where $\varepsilon_\perp>0$ and small, and where mode conversion is possible for low values of ν.

The condition for fast wave resonance on a certain magnetic surface does not depend on the antenna spectrum. On the other hand, the coupling of power from the antenna to the surface certainly depends on the relation between the antenna spectrum and the resonant wave function. As the $\varepsilon_\perp=0$ surface moves from the inside of the plasma to the outside, high mode numbers are necessary in region i), with bad coupling or cyclotron damping of the resonance as a consequence. In region ii), resonance can be obtained for lower values of ν, and mode conversion heating becomes increasingly efficient. In region iii), resonance can be found for arbitrarily low ν by going close enough to the tangent surface, also in large devices.

Thus mode conversion heating is expected to be efficient when the surface $\varepsilon_\perp=0$ intersects the midplane from a point slightly inside of the magnetic axis to the outer plasma boundary. This agrees very well with the observations in TFR [3].

In conclusion, mode conversion can occur on sections of magnetic surfaces where $\varepsilon_\perp>0$, in particular surfaces close to the one tangent to the surface $\varepsilon_\perp=0$ or near the plasma boundary. In order to use mode conversion for heating of the central region of the plasma, the $\varepsilon_\perp=0$ surface should be adjusted to intersect the midplane near the magnetic axis, preferably slightly outside of it (Fig.3). This condition replaces the algebraic resonance condition in the traditional picture as a "rule-of-thumb". The dissipation mechanisms and thus the partition of power among species also depend on the positions of the cyclotron resonances, but that question is beyond the scope of the present work.

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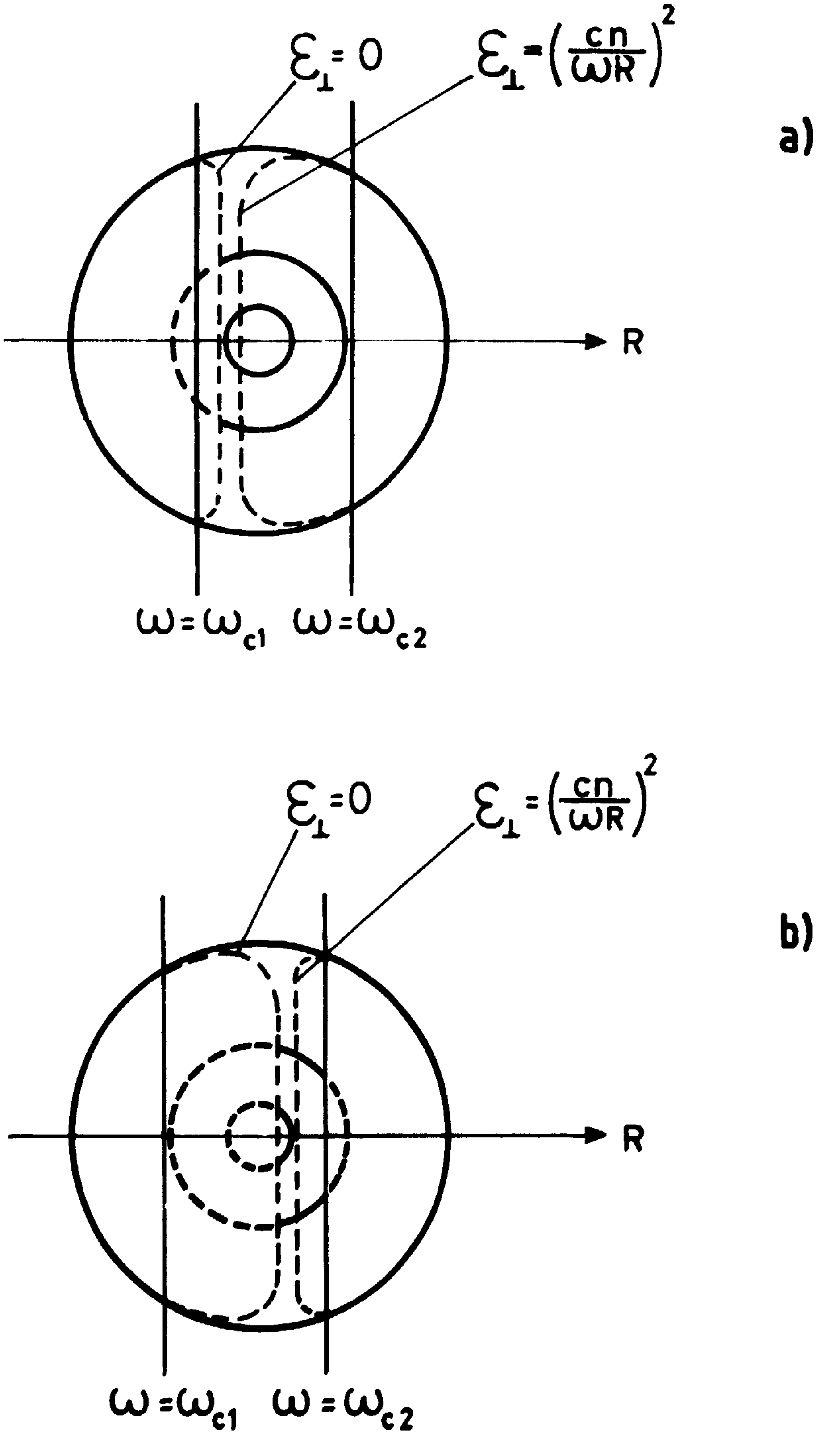
Figure captions

Fig.1 Simplified circular tokamak crossections with cyclotron resonances of two ion species intersecting the plasma. The surface where $\varepsilon_{\perp}=0$ passes the midplane on the a) inside or b) outside of the magnetic axis. The surface usually referred to as the mode conversion surface is also indicated.

Fig.2 Weighted resonance ion density profiles for a case similar to that in Fig.1a, but with the outermost cyclotron resonance located on the outside of the plasma. A parabolic profile is drawn as illustration. The intersections of the resonance profiles and the actual profile indicate the positions of mode conversion surfaces.

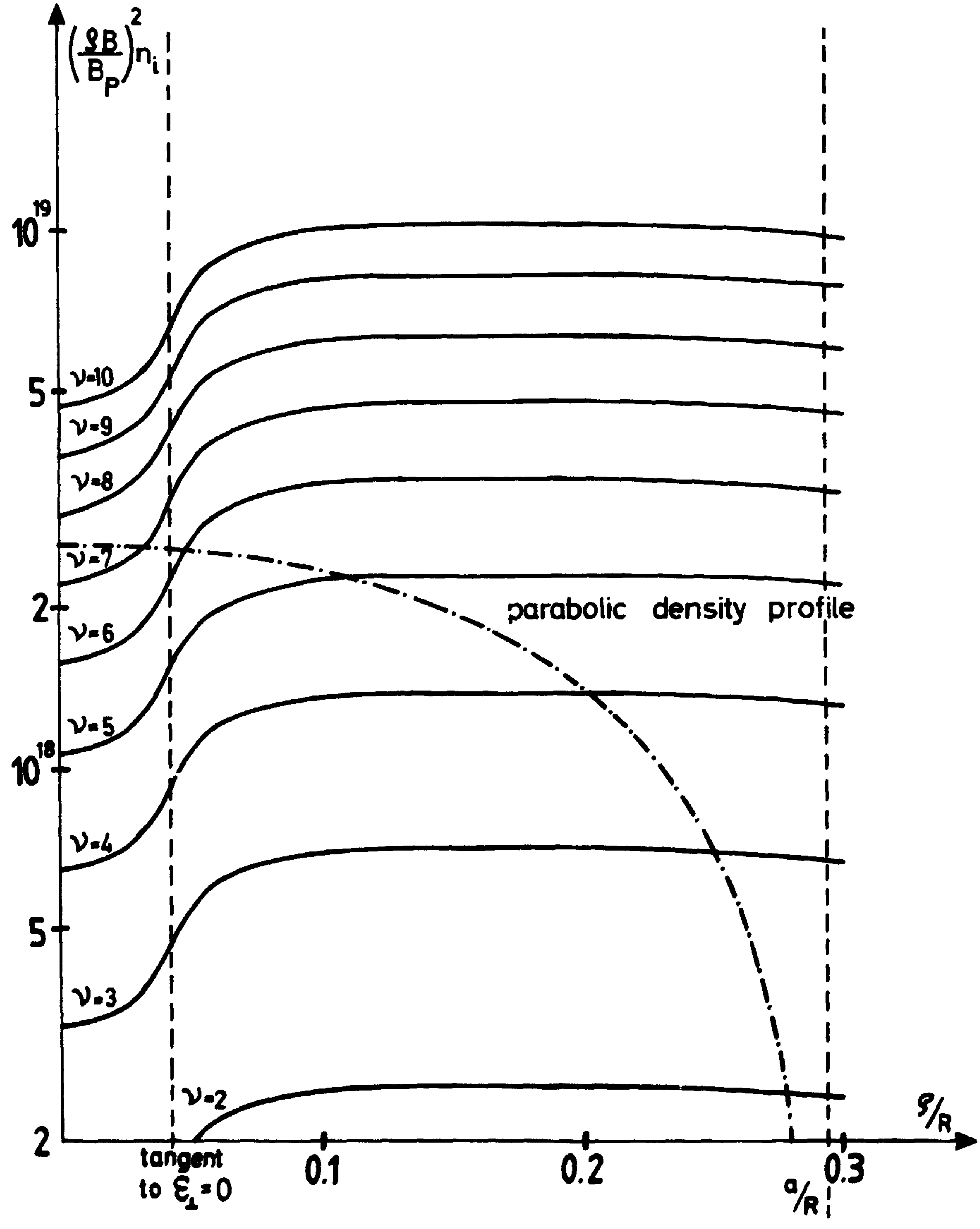
Fig.3 Suggested location of the important surfaces in order to obtain mode conversion in the core of a large tokamak plasma with a realistic antenna spectrum.

Fig. 1



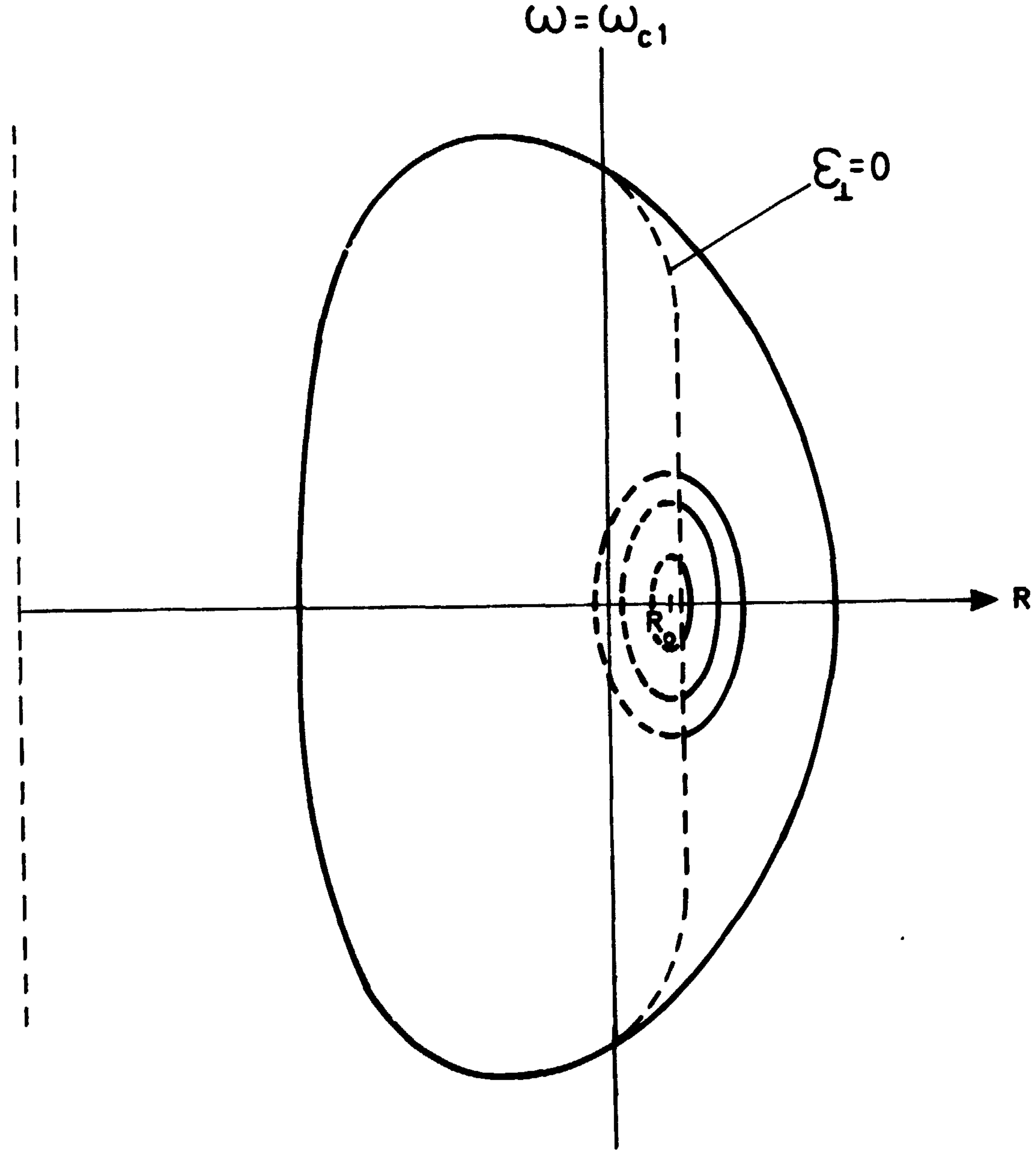
$\varepsilon_\perp = 0$
$\varepsilon_\perp = \left(\frac{cn}{\omega R}\right)^2$
a)
R
$\omega = \omega_{c1}$
$\omega = \omega_{c2}$
$\varepsilon_\perp = 0$
$\varepsilon_\perp = \left(\frac{cn}{\omega R}\right)^2$
b)
R
$\omega = \omega_{c1}$
$\omega = \omega_{c2}$

Fig.2



$\left(\frac{\rho B}{B_P}\right)^2 n_i$
10^{19}
5
2
10^{18}
5
2
$\nu=10$
$\nu=9$
$\nu=8$
$\nu=7$
$\nu=6$
$\nu=5$
$\nu=4$
$\nu=3$
$\nu=2$
parabolic density profile
tangent to $\varepsilon_\perp = 0$
0.1
0.2
0.3
a/R
ρ/R

Fig.3



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Key words: RF heating, ion cyclotron resonance, two-ion mode conversion, perpendicular ion cyclotron resonance.