PECULIARITIES OF MODE CONVERSION PHENOMENA IN BOUNDED MULTISPECIES PLASMA OF A TOKAMAK

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1. Introduction

The mode conversion (MC) of the fast wave (FW) launched from the low field side (LFS) of the tokamak appears as an attractive ICRF scenario to solve several important reactor-relevant problems, such as electron heating, local current profile control and the alpha-particles energy channeling. The reliability of the scheme was successfully verified experimentally [1-3] as well as attempts were undertaken to justify it theoretically [4,5]. In this paper a consistent 1-D picture of the MC process at the ion-ion hybrid resonance in a bounded plasma of a tokamak is discussed, which clarifies the role of the global FW interference and cavity effects in determination of the MC efficiency. Qualitative considerations are supported by simulations with 1D full-wave kinetic code "VICE" [6], which is capable to resolve ICRF waves of arbitrary scales and polarisations and to account of their interactions with particles, including high-harmonic cyclotron damping. Parameters of Tore Supra were used as an example: R_0 = 2.37 m, a = 0.75 m, B_0 = 3.8 T, H + ^{3}He (n_H/n_{He}= 0.4), $T_e(0)$ = 1.5 keV, $T_i(0)$ = 1.0 keV, $n_e(0) = 3\text{-}8\times10^{19}$ m^{-3}, f = 50-60 MHz , $k_\parallel$ = 14 m^{-1} (Note, that both $\omega = \omega_{cH}$ and MC layers, separated by a distance of ~14 cm, crossed the plasma centre).

2. Specification of the problem

The guidelines of MC studies in a tokamak plasma can be found in Budden equation analysis [7]. It predicts the existence of the closely spaced cut-off ($L = n_\parallel^2$) - resonance ($S = n_\parallel^2$) pair in the plasma centre, surrounded by two boundary ($R = n_\parallel^2$) cut-offs (Stix notations are used for dielectric tensor elements and the coordinate system orientation). Linearizing the equation and integrating the radial Pointing flux gradient over the resonance one can find, that the mode converted power $P_{mc} = \pi k_\perp \eta \left|E_y^{mc}\right|^2 / (2\mu_0\omega)$ is proportional to the square of the local "poloidal" electric field $|E_y^{mc}|$ at the resonance and to the tunneling parameter $\eta = k_\perp\Delta$ ($k_\perp$ is the asymptotic FW perpendicular wavenumber and Δ is the internal evanescent layer thickness). While monotonic dependence of η on plasma parameters is quite clear, the $|E_y^{mc}|$

behaviour (diminishing also with η) is less evident. When an isolated cut-off-resonance pair is treated [7], the only circumstance, which modifies $|E_y^{mc}|$ as compared with the falling FW amplitude is the FW evanescence near the MC region; transmitted and reflected power fractions are equal respectively to $T = \exp(-\pi\eta)$ and $R = (1-T)^2$. Accordingly, a critical value of the tunneling parameter exists $\eta = \eta_{cr} = \ln(2)/\pi \cong 0.22$ when the mode converted power fraction reaches its maximum of 25%. In a bounded plasma an additional phenomena is of paramount importance: the local value of $|E_y^{mc}|$ strongly depends on the resonance $S = n_{||}^2$ layer position relative to the global E_y field pattern, formed in plasma, as a result of FW reflections from the boundary $R = n_{||}^2$ cut-offs.

3. Peculiarities of mode conversion in a bounded plasma

Following the Tore Supra results [2], we rely on the concept of the global plasma resonator, formed by the boundary $R = n_{||}^2$ cut-offs, where competitive with MC damping mechanisms are weak. In such approach, the high field side (HFS) part of the global pattern can always be conceived as an interference of two waves with equal amplitudes: the incoming FW, transmitted through the cut-off-resonance pair and the FW, reflected from the HFS $R = n_{||}^2$ cut-off. Thus, the HFS pattern has a nature of purely standing wave for any value of η and arbitrary resonance position. In the LFS region the FW, incoming from the antenna, interferes with two waves going backwards: one is transmitted from the HFS of the resonance and another is reflected from $L = n_{||}^2$ cut-off. The amplitudes of these backward going waves depend on η in opposite manner, being equal at $\eta = \eta_{cr}$, and their phase difference is sensitive to the resonance position. It is clear, that if the resonance is located near the antinode of the global $|E_y|$ field pattern, the phases are opposite and the waves cancel each other; thus, the LFS pattern is represented solely by the FW, travelling from the antenna to the resonance. Oppositely, if the resonance coincides with the global field node and P_{mc} is negligible, the radial Pointing flux equals to zero, which means that the backward going waves have the same phases and the sum of their amplitudes is equal to the amplitude of the falling FW; the LFS pattern (as well as the entire pattern) has a purely standing wave nature. These peculiarities of the $|E_y|$ pattern were clearly revealed during the "VICE" simulations for fixed $\eta \cong \eta_{cr}$ (Fig.1). The frequency variation was chosen for scanning the MC layer in the radial direction (This scan did not affect the tunneling parameter, which was controlled by the plasma density adjustment: $\eta_{cr} = 0.22$ when $n_e(0) \cong 4\times10^{19}$ m^{-3}). The corresponding behaviour of specific MC characteristics is shown in Fig. 2, where (a) is the squared ratio of the local $|E_y^{mc}|$ value to the "falling" FW amplitude $|E_y^f| = (|E_y^{min}| + |E_y^{max}|)/2$, (b) is the LFS travelling wave ratio $G = |E_y^{min}| / |E_y^{max}|$, (c) is the electron damping "figure of merit"

$Q_e = \omega W/P_e$ and (d) is the fraction of the total power, absorbed by electrons (E_y^{min} and E_y^{max} are defined in Fig. 1(d); $P_{e,i}$ is the RF power, absorbed by individual species and $W = 1/(16\pi)\int(|\mathbf{E}|^2+|\mathbf{B}|^2)\,dx$ is the RF electromagnetic energy stored in plasma.) Dashed line in Fig. 2(c) represents an estimate of Q_e, accounting only of direct FW ELD and TTMP damping.

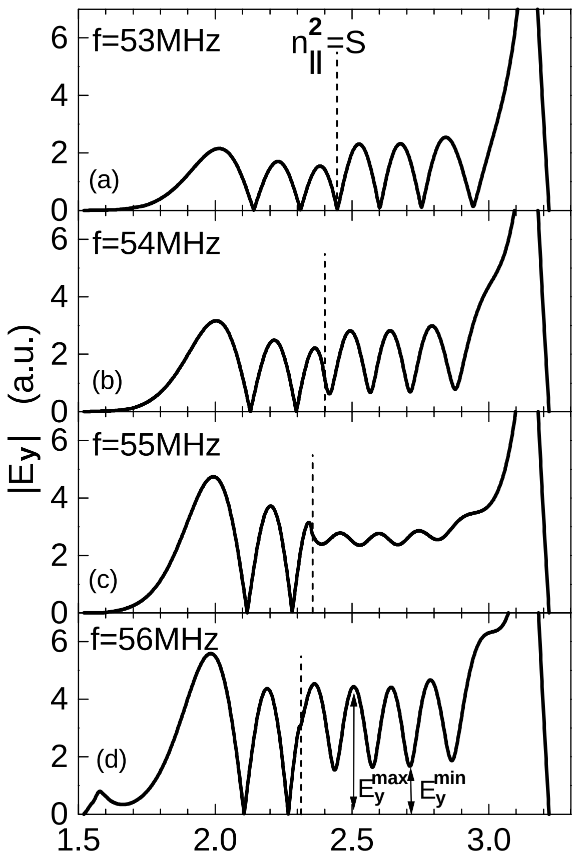

Fig.1

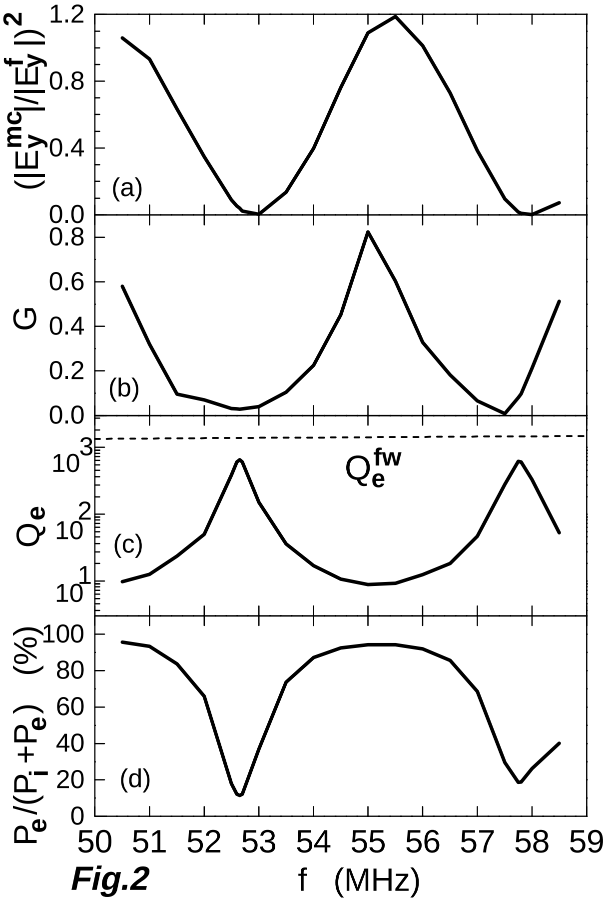

Fig.2

It is clear, that as $|E_y^{mc}|$ increases (the MC layer is closer to the global antinode), the reflected power flux vanishes ($G\to1$), the electron MC damping reaches maximum (the lowest Q_e), dominating over the ion cyclotron FW damping. The discussed phenomena introduce an important feature of the global resonator cavity modes behaviour: with $G\to1$ no cavity mode formation is possible, as there are no LFS FW reflections. Thus, the cavity modes build-up should strongly depend on the MC layer position relative the global pattern. Figure 3 demonstrates this effect: the plasma minor radius was varied to match the global resonator at $a = a_c$ (this procedure affects neither the tunneling factor nor the MC layer position) for three different frequencies in conditions of $\eta = \eta_{cr}$ (see also Fig.1(a-c)). The crucial role of the tunneling parameter in the global pattern modification can be seen on Fig. 4, where the frequency was matched near f = 55 MHz for each η value to fit the maximum MC conditions (maximize $|E_y^{mc}|$) . As the backward going FWs for $\eta \neq \eta_{cr}$ always have different amplitudes in LFS region, the standing wave component never vanishes here, although being minimal when the resonance coincides with the global antinode. Besides with increasing η value, the field structure turns to be perceptibly distorted by a strong local FW evanescence near the resonance and for $\eta >> \eta_{cr}$ the global node always follows the $S = n_{||}^2$ resonance.

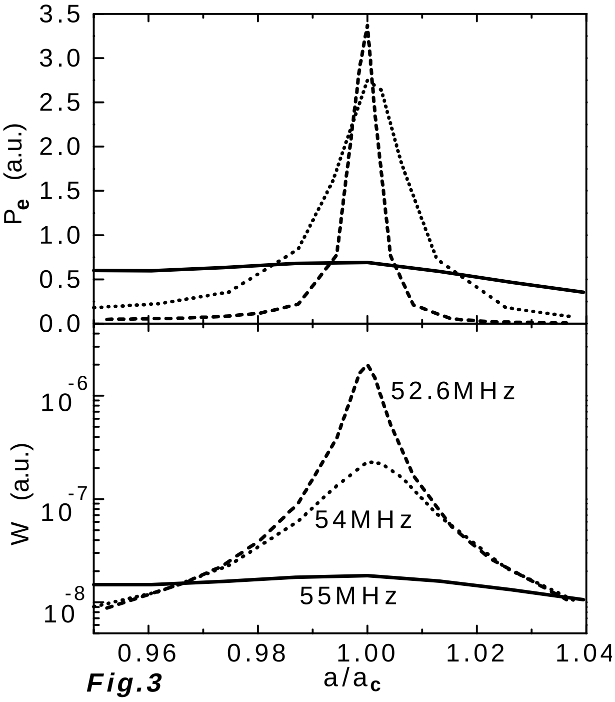

Fig.3

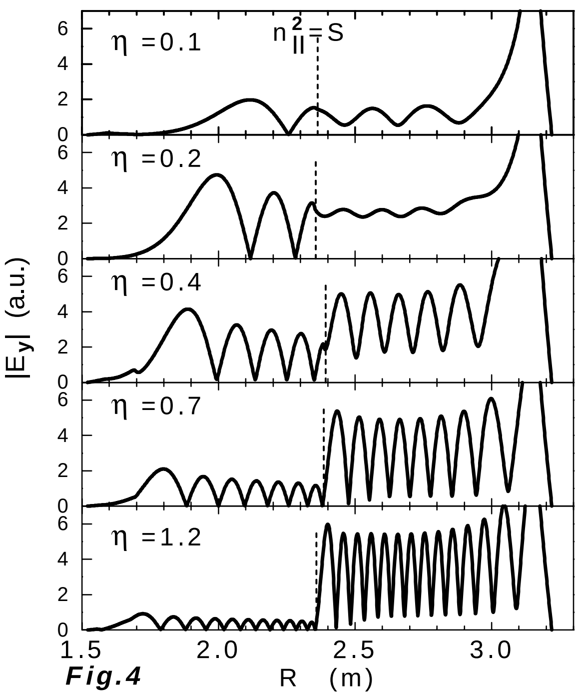

Fig.4

4. Conclusions

Our analysis, along with its generalising meaning, provides the important conclusion that in a bounded plasma optimum MC regimes are attainable at $\eta \cong \eta_{cr}$ when the MC layer coincides with the global $|E_y|$ antinode. In contrast to the previous treatments [4,5], this requirement does not impose any constraints on $k_{||}$ choice. Thus, the MC scheme applicability can apparently be extended to a wider range of excited FW parallel wavelengths.

References

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