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Excitation of Electron Bernstein Waves in MAST

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For a MAST plasma, it is envisaged to launch a wave with f=60GHz in the ECR band. The mid-plane launch of such a wave has been studied by B. Lloyd et al [1]. For a central density lower than $2.5\times10^{13}\text{cm}^{-3}$, they showed that the linearly polarized X-mode at perpendicular incidence penetrates the whole plasma column and it is absorbed at the 3rd and the 2nd electron cyclotron resonance regions situated symmetrically near the centre of the plasma.

In an over dense plasma, both the X and O modes cannot penetrate to the plasma centre since they are reflected at their respective cut-offs. For a mid-plane launch of such a very short wavelength 60 GHz wave, only the O-X-EBW conversion process [2] can be used for the excitation of electron Bernstein modes (EBW). Since these modes have no density limit, they can penetrate to the core plasma.

To estimate the absorbed power at oblique incidence we use the analytic WKB expression for the penetration of the O-mode through the plasma resonance and its subsequent conversion to the X mode and then the conversion to the EBW [2,3]. We have also solved the full set of Maxwell equations by the finite element method [4] for wave propagation in an inhomogeneous cold plasma slab.

The wave incidence geometry is shown in Fig. 1. Here α is the angle of incidence, β is the angle between E^{inc} and the plane of incidence, γ is the the angle between B_{total} and the plane of incidence. The dimensionless components of wavevector can be expressed as $N_y = k_y/k_{vac} = \sin\alpha\sin\gamma$, $N_z = k_z/k_{vac} = \sin\alpha\cos\gamma$ and $k_{vac} = c/\omega$..

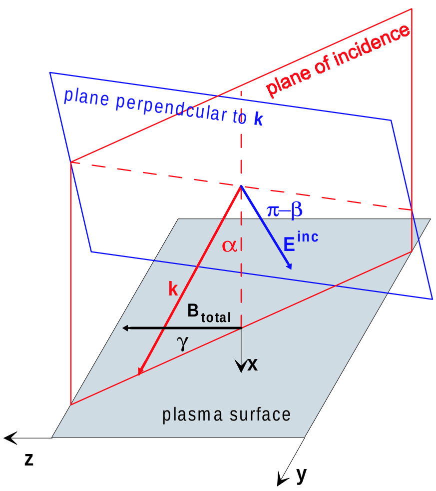

Fig. 1. Geometry of a linearly polarized electromagnetic wave incident on a plasma.

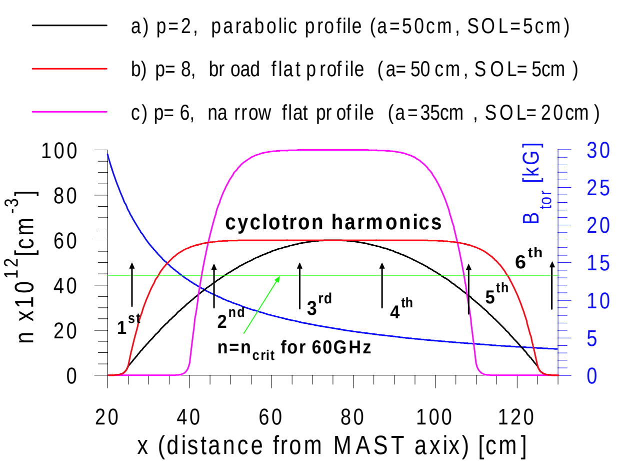

Fig. 2. The density and magnetic field profiles assumed for computation of ECR power absorption in MAST .

Only preliminary data about actual density and magnetic field profiles are known for MAST so, in numerical computation, we consider three model situations depicted in Fig. 2 (here

$n \sim n_{centr}(1-(\overline{x}/a)^p)$, $B = B_0 * R/(R+\overline{x})$, where $\overline{x} = x - 20 - a - SOL$, R and a are the large and small radius, respectively, and SOL is the width of the scrap-off layer, R=70cm and $B_0 = 6.3kG$). The narrow flat profile, corresponding to the formation of the H mode transport barrier, extends, in reality, much neared to the central rod on the left side , but, in the computation, only the low field side of the profile is important.

Deeper insight into the wave propagation follows from the WKB solution of a slab model for a tokamak plasma. From Fig. 3, it is clear that the X-mode is reflected at the R-cut-off (here $\omega_{pe}^2 = \omega(\omega-\omega_{ce})(1-N_z^2)$, where ω_{pe} is the electron plasma frequency and ω_{ce} is the electron cyclotron frequency) and the O-mode penetrates through the plasma resonance because the evanescent layer between the plasma resonance and the L-cut-off ($\omega_{pe}^2 = \omega(\omega+\omega_{ce})(1-N_z^2)$) disappears for the optimal N_z (i.e., $\alpha = 43^o$). The O-mode converts to the fast branch of the X-mode which, deeper in the plasma,is then reflected back as the slow branch of the X-mode. In our model, this wave is then fully absorbed at the upper hybrid resonance region ($\omega_{pe}^2 = \omega^2 - \omega_{ce}^2$) due to weak ad hoc collisions ($\nu/\omega \ll 1$). In reality, the slow branch of the X-mode converts to the electron Bernstein wave at the upper hybrid resonance. The EBW propagates back towards the plasma center where it is absorbed at the ECR region.

The transmitted O-mode power through the plasma resonance region at oblique incidence in a weakly inhomogeneous magnetized plasma (using slab geometry) is [2,3]

$$|T| = exp\left\{-\frac{\pi k_{vac}}{8\kappa_p}\sqrt{\frac{2\omega}{\omega_{ce}}}\left[\left(\frac{\omega_{ce}}{\omega}\right)^2\left(1-\left(\frac{N_z}{N_z^{opt}}\right)^2\right)^2 + \frac{2\omega_{ce}}{\omega}N_y^2\right]\right\}, \quad (1)$$

where $\kappa_p = \frac{1}{n_{crit}}\frac{\mathrm{d}n}{\mathrm{d}x_p} = L_n^{-1}$, x_p is the position of the plasma resonance, $N_z^{opt} = \sqrt{\frac{\omega_{ce}}{\omega+\omega_{ce}}}$.

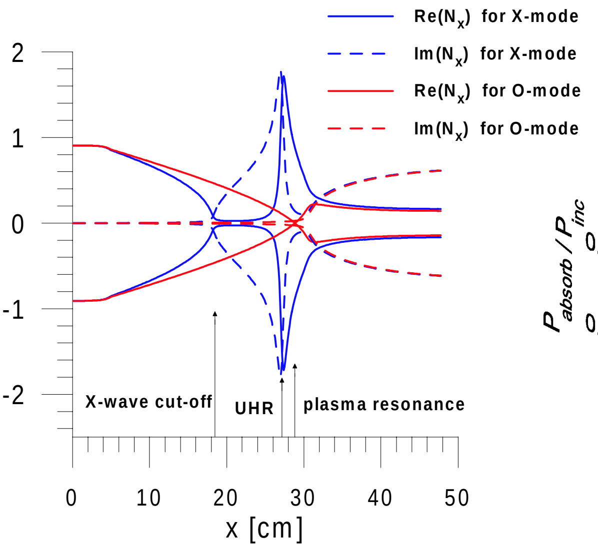

Fig. 3. WKB solution of the cold dispersion equation for optimum launch with $N_y = 0$, $N_z = 0.425$ ($\alpha = 25^o$), f=60GHz, $\nu/\omega = 0.01$ and a simple parabolic density profile from Fig. 2a is used.

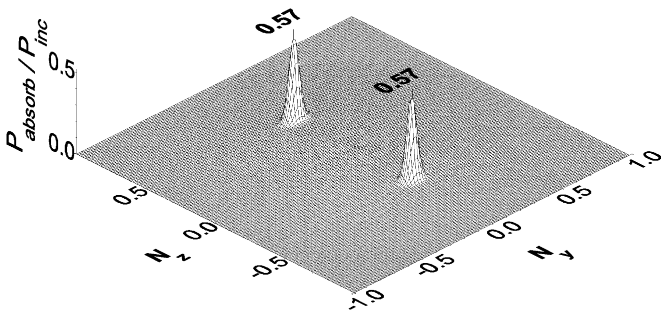

Fig. 4. Power absorbed in a MAST plasma at oblique incidence of linearly polarized wave ($\beta = 0$). The same case as in Fig. 3 but only very low collisionality $\nu/\omega = 0.00005$ is needed to suppress unphysical damping of O and X-modes out of the upper hybrid resonance region.

For the 60GHz wave and parabolic density profile ($L_n = 37cm$), only a very well collimated incident beam of waves will penetrate through the plasma resonance region (the angular deviations from the optimal ray are only $\pm 2^o$ for $1/e$ decrease of T). These WKB results are confirmed by the full wave solution of the problem (see Fig. 4)

On entering the plasma, the wave is split into the X- and O-modes. For our parameters, the X-mode is immediately reflected back and only the incident power that is converted into the O-mode can be absorbed. The relative amplitudes of the X- and O-modes are dependent on the polarization of the incident wave. As it is seen from Fig. 5, one can basically achieve total absorption for an obliquely incident circularly polarized wave. In Fig.5 the parameter b/a correspond to the ratio of the major to minor axis of the polarization ellipse and β is the angle between the major axis and the plane of incidence.

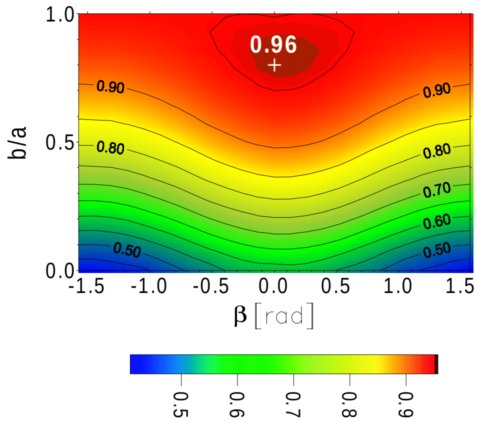

Fig. 5. Power absorbed in MAST plasma at the oblique incidence of elliptically polarized wave (f=60GHz) launched at the mid-plane on the low field side and at the optimum angle ($N_y = 0, N_z = 0.42$) and the same parameters as in Fig. 4

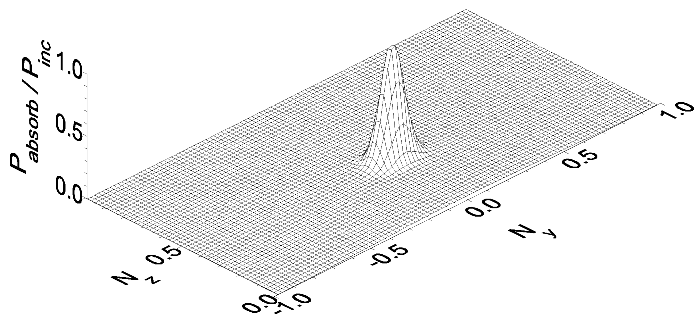

Fig. 6. Absorbed power in MAST plasma at oblique incidence of circularly polarized wave rotating counter-clockwise (f=60GHz, $B_0 = 6.3$kG, $\nu/\omega = 0.0001$ and broad flat density profile from Fig. 2b). 1/e decrease of T for deviations $\delta_{tor} = \pm 3^o$ and $\delta_{pol} = \pm 4.5^o$.

Even for the broad flat profile (Fig. 2b) with rather steep density gradient at the plasma resonance region (L_n =15cm), the angular width of the incident beam, which could penetrate through the plasma resonance region, is not that much large (see Fig. 6). However, the optimal ray of circularly polarized wave with $N_y = 0, N_z = 0.39$ ($\alpha = 23^o$) and $N_x = \sqrt{1 - N_y^2 - N_z^2}$ penetrates fully and 98% of its power is absorbed. In this case, actual absorption take place at the 5th harmonic. But this harmonic is inconveniently located near the plasma edge (see Fig. 2). While the Bernstein modes do not have a density limit, they are trapped between two consecutive electron cyclotron harmonic regions, being reflected back into the denser plasma at the higher harmonic and fully absorbed at the lower harmonic.

It seems that only for a narrow flat profile having L_n=4.9cm will one find suitable conditions for the absorption of a rather angularly broad beam of waves. From Fig. 7 we see that the circularly polarized wave with the electric vector rotating counter-clockwise (for $N_z > 0$ and clockwise for $N_z < 0$) having the optimal angle of incidence $\alpha = 24^o (N_y = 0, N_z = 0.41)$ can fully penetrate plasma resonance region. Angular deviation around this optimal ray are acceptably large ($\delta_{tor} = \pm 7$ and $\delta_{pol} = \pm 9$ for $1/e$ decrease of T). Even shaper profiles have been seen on MAST for H mode regimes and thus the acceptable angular deviation δ_{tor} and δ_{pol} could be even larger. Because both the plasma and the upper hybrid resonance regions are situated between the $4th$ and $5th$ harmonic, the EBW is absorbed near the plasma center.

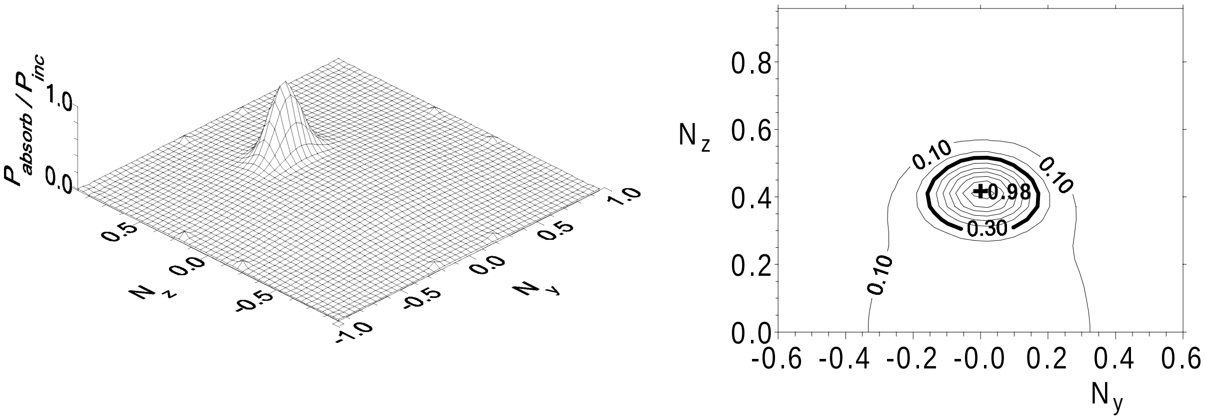

Fig. 7. Power absorbed in MAST plasma at the oblique incidence of circularly polarized wave launched at the mid-plane on the low field side (f=60GHz, $B_0 = 6.3$kG, $\nu/\omega = 0.001$ and narrow flat density profile from Fig. 2c)

Wave propagation is strongly influenced by the magnetic shear, and this is very important in spherical tokamaks; namely the optimal direction of incident beam is dictated by the magnetic field direction in the plasma resonance region. Also it seems that the choice of frequency (60GHz) was unfortunate (but logical, since all the equipment has been available for many years ago!). A lower frequency (e.g. 30GHz) would be more appropriate to launch into the plasma (for sufficiently sharp density profiles even the X-mode at normal incidence would tunnel through the evanescent region between the R-cut-off and UHR) and there would be no problems with the angular width of the incident beam. Both these problems have been solved, and will be presented at the Tucson conference [5].

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