



Original Article

Study on resonant electron cyclotron heating by OSXB double mode conversion at the W7-X stellarator

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ABSTRACT

Electromagnetic waves potentially have been used to heat overdense nuclear fusion plasmas through a double mode conversion from ordinary to slow extraordinary and finally to Electron Bernstein Wave (EBW) modes, OSXB. This scheme is efficient and has not any plasma density limit of electron cyclotron resonance heating due to cut-off layer. The efficiency of conversion depends on the isotropic launching angles of the microwaves with the plasma parameters. In this article, a two-step mode conversions of OSXB power transmission efficiency affected by the fast extraordinary (FX) losses at upper hybrid frequency are studied. In addition, the kinetic (hot) dispersion relation of a overdense plasma in a full wave analysis of a OSXB in Wendelstein 7X (W7-X) stellarator plasma has been numerically simulated. The influence of plasma dependent parameters such as finite Larmor radius, electron thermal velocity and electron cyclotron frequency are represented.

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1. Introduction

Nuclear fusion energy is the future energy demand inevitably to its large fuel supply, fairly safe in technology and ultimately, without any serious environmental problems. Up to now, several methods have been developed and used among which Magnetic Confinement Fusion (MCF) by Tokamak [1,2] and Stellarator [3,4], are the most promising. High yield nuclear fusion reactions require high temperature and pressure, necessary for the ignition. However, to anticipate such high temperature, the core of magnetically confined overdense plasma must be heated.

Microwave sources have been used to heat the core of overdense magnetized plasma [5–8]. One of the ways to do that, is the OSXB scheme in which, microwaves energy transform to the overdense magnetized plasma by means of electron cyclotron resonance heating (ECRH), [9–12]. To implement OSXB scheme, one has to use mode conversion scheme in which an O mode is launched obliquely (with respect to the background magnetic field) from the low field side. If the angle of incident wave is correctly chosen, the O mode penetrate into plasma evanescent region coincident with SX mode at the L cutoff. The SX mode travel back to the lower density plasma

up to Upper Hybrid Resonance (UHR) in which SX mode directly converts to the EBW mode, propagating to the plasma core without any density cutoff and, ultimately, it will be absorbed at the plasma center. Is there any inefficiency in this method that is not only due to plasma high density, however, most of the fusion devices employ comparatively low magnetic fields [13].

The process of OSXB mode conversion was first proposed by Preinhaelter and Kopecky, and later used by Laqua et al., to heat overdense magnetized plasma on the W7-AS stellarator [14–16]. The formalism of OSXB mode conversion together with parametrical influences on two-steps OSXB modify transmission function T_{mod} for Wendelstein 7-X (W7-X) stellarator was presented in previous publication [17].

In this article, a double mode conversion OSXB will be analytically and numerically studied using Wendelstein 7-X (W7-X) stellarator data, $f = 140$ GHz, $B = 2.5$ T. The kinetic effect has been fully considered in the dispersion relation of cold plasma and simulated for perpendicular launched. The OSXB power transmission efficiency at upper hybrid frequency is fully discussed. The influence of plasma dependent parameters such as finite Larmor radius, electron thermal velocity and electron cyclotron frequency are represented. Finally, all calculations have been carried out using mathematics software with MacIntosh computer cori 7.

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2. The formulation of the OSX mode conversion

The ordinary to slow extraordinary (OSX) conversion mode begins by launching an O mode wave from low field side of vacuum chamber which ultimately, the O mode penetrate into plasma evanescent region and coincide with SX mode at the L cutoff, $\omega = \omega_p$. A second conversion happened at (UHR) under special condition, $\omega = \omega_L$, which eventually converts to the EBW mode. The EBW mode can penetrate into overdense plasma core without any cut-off conditions.

As OSX mode conversion mode scheme is considered here, a

$$N_{\perp}^2 = 1 - \frac{2X(1-X)}{2(1-X) - Y^2 \sin^2 \theta \pm \Gamma} \quad (3)$$

with $\Gamma = [Y^4 \sin^4 \theta + 4(1-X)^2 Y^2 \cos^2 \theta]^{0.5}$ and $X = \frac{\omega_p^2}{\omega^2}$ and $Y = \frac{\omega_c}{\omega}$, where ω_p is the plasma frequency and ω_c is an electron cyclotron frequency. If the obliquely incident wave propagates towards the cutoff layer, only the perpendicular wave vector goes to zero at the cutoff layer and the parallel wave vector remains unchanged. So, the perpendicular refractive index can be presented as [21,22];

$$N_{\perp}^2 = 1 - N_{\parallel}^2 - X - \frac{XY}{2(1-X-Y^2)} \left[Y(1+N_{\parallel}^2) \mp \left(Y^2(1-N_{\parallel}^2)^2 + 4N_{\parallel}^2(1-X) \right)^{0.5} \right] \quad (4)$$

cold plasma dispersion relation has to be exploited. In a simple and straight forward approximation, the solution given by Altar-Appleton Hartree is summarized as follows [18,19];

$$AN^4 - BN^2 + C = 0 \quad (1)$$

where $A = S \sin^2 \theta + P \cos^2 \theta$, $B = (S+D)(S-D) \sin^2 \theta + P(S+1+\cos^2 \theta)$ and $C = P(S+D)(S-D)$. The solution of Eq. (1) is given by

$$N^2 = \frac{B \pm \sqrt{B^2 - 4AC}}{2A} \quad (2)$$

The positive and negative signs indicate the OSX propagations, respectively. The solution of Eq. (2), can also be presented in the following form, [20];

In Eq. (4), N_{\perp} and N_{\parallel} are the perpendicular and the parallel component of refractive indexes with respect to the applied magnetic field, respectively. At the cutoff layer, $X = 1$, the O mode reaches the deep in the plasma layer, when the quantity of the refractive index has an optimum value $N_{z, \text{opt}}$. At this situation, the O mode will transfer with higher value of power transmission to SX mode, [1]. The evolution of the perpendicular refractive index N_{\perp}^2 as a function of the normalized plasma frequency X (or density X) for seven different parallel refractive index N_{\parallel} is depicted in Fig. 1.

The efficiency of ordinary to slow extraordinary mode conversion is highly depending upon the angle between the direction of wave propagation and the external magnetic field. Conversely, the OSX mode conversion efficiency with respect to the N_z is given by Mjølhus formula [23];

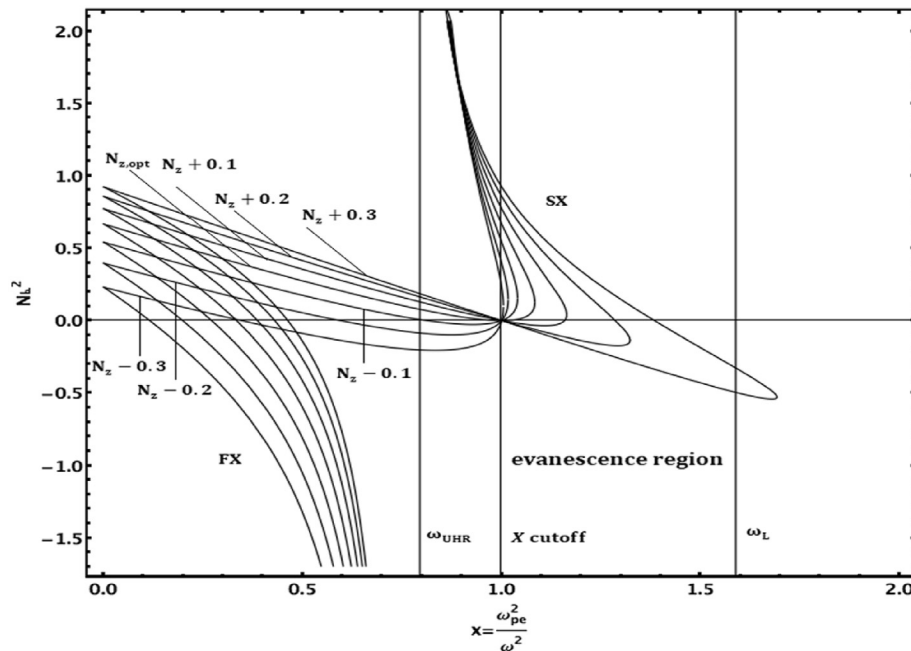


Fig. 1. Behavior of the normal component of the refractive index as a function of the normalized plasma frequency for OSX mode conversion, $\theta_{\text{opt}} = 54^\circ$ obtained for W7-X stellarator, $f = 140$ GHz and $B = 2.5$ T.

$$T_{OSX} = \exp \left[-\pi k_0 L_n \sqrt{\frac{Y}{2}} \left(2(1+Y)(N_z - N_{zopt})^2 + N_y^2 \right) \right] \quad (5)$$

The size of conversion window depends much on the lurching angle and the tunneling length which is between an O and L cutoff, Fig. 2. As the most of the plasma heating parameters are controlled by heating scenario, the only parameters that can affect the conversion of the OSX mode is the length scale of the density gradient $L_n = \frac{n_e}{\frac{\partial n_e}{\partial x}}$. Therefore, the process of conversion is more effective when L_n is small i.e., $\frac{L_n}{\lambda_0} \geq 1$, [24]. Here, n_e is the electron density, $\frac{\partial n_e}{\partial x}$ the density gradient, and λ_0 is the vacuum wavelength of the incident microwaves.

In order to take into account the effect of plasma turbulence at the cutoff layer, dealing with power transmission, we survey a statistical approach for the poloidal components and a probability density function [15]. By including the probability density function to the transmission coefficient function, the modified ordinary to slow extraordinary transmission can be obtained by the following;

$$T_{mod}(N_{||}) = \int_{-1}^{+1} T(N_{||}, N_{||}) P(N_y) dN_y \quad (6)$$

where, $P(N_y) = \frac{\lambda_y}{\sqrt{2\pi}\sigma_x} \exp \left(-\frac{N_y^2 \lambda_y^2}{2(1-N_y^2)\sigma_x^2} \right) (1-N_y^2)^{-\frac{3}{2}}$, and λ_y is the poloidal correlation length and $\sigma_x = L_n \frac{\Delta n}{n}$ is the standard deviation of the fluctuation amplitude [25]. Fig. 2 presents a comparison of the OSX mode conversion efficiency as a function of normalized $\frac{N_z}{N_{zopt}}$, with and without plasma turbulence at the cutoff layer.

If the surface of the cutoff layer is smooth, the wave vector will change directly without any scatterings. If there is any roughness, the wave scattering will take place [26], and other modes will be presented.

3. The efficiency of the OSXB mode conversion

The SX mode emerges from evanescent region and propagate towards the UHR. At this region, the new FX mode emerged from SX, is tunneling through the evanescent layer between the UHR and RH (right hand) cutoff and goes out of the plasma and, therefore,

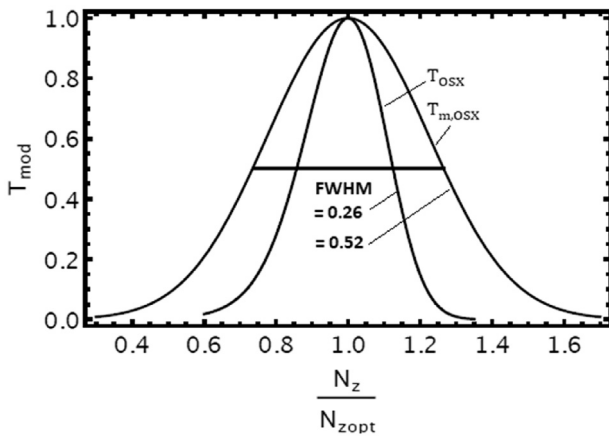


Fig. 2. The OSX mode conversion efficiency as a function of normalized $\frac{N_z}{N_{zopt}}$, with and without plasma turbulence at the cutoff layer, $B = 2.5$ T, $\lambda = 2$ mm, $Y = 0.499$, $\theta = 54^\circ$, $L_n = 2$ mm, $N_y = 0$ for T_{OSX} , and for the modified, $T_{m,OSX}$, $\lambda_y = 2$ mm, $\frac{\Delta n}{n} = 3\%$, and $f = 140$ GHz, in W7-X Stellarator.

the wave is lost. So, the part of SX at UHR will convert to electrostatic mode or B mode (Electron Bernstein wave). At this region, the refractive index goes to infinity, and the wavelength becomes shorter. Here, a small phase velocity will be produced. As the wave phase velocity is fairly comparable to the electron thermal velocity, the cold plasma model cannot support all the physical mode produces. Therefore, we have to include the kinetic effects into dispersion relationship.

The overall efficiency of the OSXB mode conversion is affected by the FX losses. The Budden parameter η in the exponential evaluated the losses as;

$$T_{OSXFX} = \exp \left[-\pi \left(\frac{\omega_{ce} L_n}{C\alpha} \right) \sqrt{[1 + \alpha^2 - 1]} \right] \quad (7)$$

where $\alpha = \left[\frac{\omega_{pe}}{\omega_{ce}} \right]$, and $\eta \approx \left(\frac{\omega_{ce} L_n}{C\alpha} \right) \sqrt{[1 + \alpha^2 - 1]}$ is the reduced Budden parameter, [1,27,28]. Thus, the estimated overall efficiency of the OSXB mode conversion, can finally be written as;

$$T_{OSXB} = T_{OSX}(1 - T_{OSXFX}) \quad (8)$$

As depicted in Fig. 3.

4. OSXB mode conversion

In the cold plasma study, the thermal velocity of the electrons is assumed to be zero, so the Larmor radius of their gyro-orbits around magnetic field lines equal to zero. In the hot overdense magnetized plasma, the electrons of the plasma have thermal velocity. Therefore, the nature of the EBW's are the electrostatic or space charge plasma waves with the longitudinal character and originally, created by the collective gyro-motion of the electrons. However, as the OSX approaches UHR layer, $\omega_{UHR}^2 = \omega_c^2 + \omega_p^2$, its wavelength becomes small on the same order as the electron Larmor radius, $r_L = \frac{v_{th}}{\omega_{ce}}$, where ω_c is electron cyclotron frequency and $v_{th} = \sqrt{\frac{2KT}{m_e}}$ is the electron thermal velocity. In this situation, the OSX modes couple to EBW at the UHR layer. As a result, the EBW propagates away from the resonance layer and moves toward the overdense plasma regions and plasma core and damps at electron cyclotron resonance frequencies if the propagation is perpendicular to the background magnetic field. As a consequence of the EBW interaction with the electrons at resonance frequency $\omega = n\omega_c$, the electrostatic wave will be strongly transfer energy to the electrons, thus the mechanism of ECRH heats the plasma [29–31]. Here, we

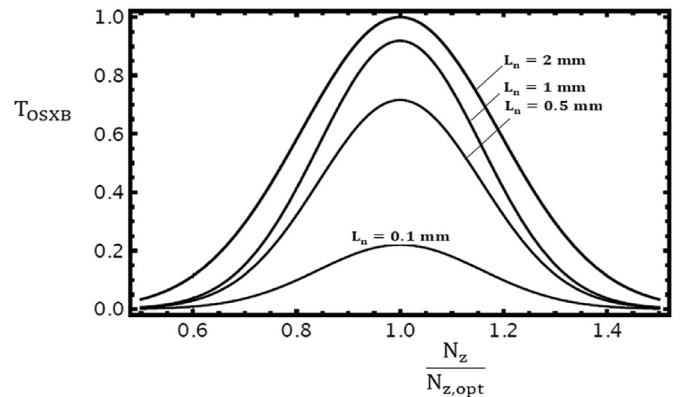


Fig. 3. Mode conversion of OSXB as a function of normalized refractive index $\frac{N_z}{N_{zopt}}$, $L_n = 0.1, 0.5, 1, 2$, mm, $f = 140$ GHz, and $B = 2.5$ T, in W7-X Stellarator.

assume that the electron velocity distribution has a Maxwellian form, the equation of nonzero electron temperature, for the propagation perpendicular to the background magnetic field \mathbf{B} , where $k_{\parallel} = 0$, can be written as the Bernstein Mode;

$$\bar{\mu} = \frac{\omega_{pe}^2}{\omega_{ce}^2} e^{-\bar{\mu}} \sum_{n=-\infty}^{+\infty} \frac{n I_n(\bar{\mu})}{\left[\frac{\omega}{\omega_{ce}} - n \right]} \quad (9)$$

Which has solution for both ω and k real [31]. To obtain the resonant frequencies, Eq. (9) should be solved numerically and for the convenient, to rewrite Eq. (9) in the form

$$\bar{\mu} = 2 \frac{\omega_{pe}^2}{\omega_{ce}^2} e^{-\bar{\mu}} \sum_{n=+1}^{+\infty} \frac{n^2 I_n(\bar{\mu})}{\left[\left(\frac{\omega}{\omega_{ce}} \right)^2 - n^2 \right]} \quad (10)$$

where $\bar{\mu} = \frac{k_B T_e}{m_e} \frac{k^2}{\omega_{ce}^2}$, k_B is Boltzmann's constant, T_e is the electron temperature, k is the perpendicular wave, m_e is the electron mass, I_n the n th order modified Bessel function, and $\omega = n\omega_{ce}$ for integer n .

There are three cases for the values of $\bar{\mu}$; $\bar{\mu} \ll 1$ satisfied for cold plasma conditions, $\bar{\mu} < 1$ warm plasma, and $\bar{\mu} > 1$ presents hot plasma conditions. The first and probably the second conditions involve cold plasma dispersion and the integer value of n in the equation of the sum Eq. (10), if $n = 1$, the Bessel function in $I_{1,-1} = \frac{\bar{\mu}}{2}$ and $\frac{\omega}{\omega_{ce}}$ is not close to n , only the term $n = 1$ in the infinite series on the right-hand side of (6), contributes significantly, which other terms are very small.

Therefore, Eq. (9) for $\bar{\mu} \ll 1$, ω can be derived as, $\omega = (\omega_{pe}^2 + \omega_{ce}^2)^{\frac{1}{2}}$, which is the UHR frequency. As seen, for the ratio $\frac{\omega_{pe}^2}{\omega_{ce}^2} = 1$, the value of $\frac{\omega}{\omega_{ce}}$ correspond to the UHR, Therefore, the value of $n = 1$, is not the solution of the modified Bessel function. This frequency is so predicted by cold plasma model. The hot plasma theory verify the results acquired by the cold plasma model in the zero temperature limit. In addition, the dispersion relation Eq. (10) can be predicted other resonance frequency in $\bar{\mu} \ll 1$ (in the zero temperature limit) by taking $\omega = n\omega_{ce}$ and for $n \geq 2$, which cannot be predicted by the cold plasma model.

Each n^{th} term in Eq. (10) has an important role in resonance frequency at any harmonics such as $\omega = n\omega_{ce}$, $n \geq 2$, and $\bar{\mu} \ll 1$. For $\bar{\mu} < 5$, the resonance condition is, also, satisfied and each interval has several resonance frequencies as $\left(\frac{\omega_{pe}}{\omega_{ce}} \right)^2$ varies. As $\left(\frac{\omega_{pe}}{\omega_{ce}} \right)^2$ increases, the resonance pick moves towards the main axes and upper limits of the n . For $\bar{\mu} \gg 1$, one should deal with the asymptotic solution in the modify Bessel function.

The plot of $\frac{\omega}{\omega_{ce}}$ as a function $\bar{\mu}$ is depicted in Fig. 4 for the ratios $\frac{\omega_{pe}^2}{\omega_{ce}^2} = 1, 3, 5, 8, 10$.

Having considering hot dispersion relation as a function $F\left(\frac{\omega}{\omega_{ce}}, \bar{\mu}\right)$, we have depicted this function in term of $\frac{\omega}{\omega_{ce}}$ to show that the resonance heating occurs in $\frac{\omega}{\omega_{ce}} = 2$ up to 6 at constant value of $\bar{\mu} = 2.4$, Fig. 5. However, there is a good agreement between Figs. 4 and 5. In other words, one can see no resonance in $n = 1$ and apparently for $n \geq 7$ moderate or rear resonance heating occurs.

Regarding to the Fig. 4, one can solve numerically the hot plasma dispersion relation by taking $\frac{\omega_{pe}^2}{\omega_{ce}^2} = 3.59$, for example, to obtain $\bar{\mu}$ as a function of plasma densities for various plasma temperatures. The result of such calculations is displayed in Figs. 6 and 7.

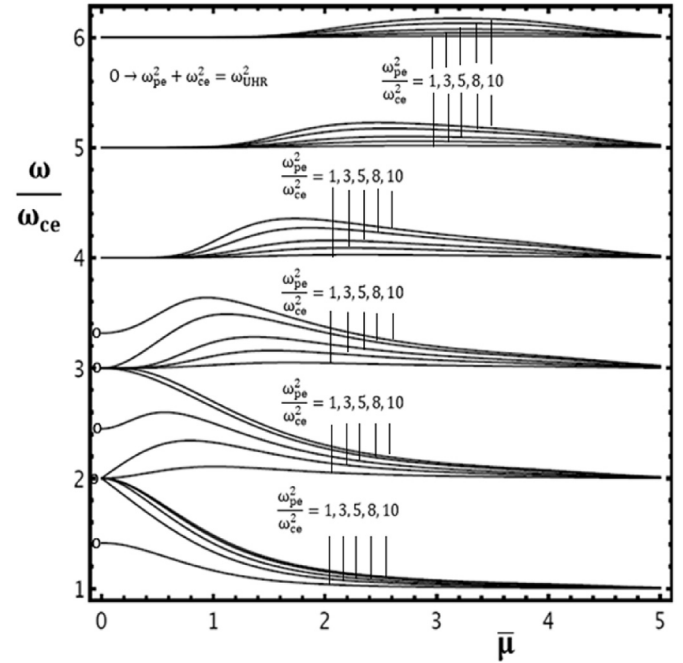


Fig. 4. Dispersion relation of the electrostatic EBW for perpendicular propagation at different values of the parameter $\frac{\omega_{pe}^2}{\omega_{ce}^2}$ as a function of $\bar{\mu}$.

5. Results and discussion

A double mode conversion, Ordinary (O) to slow extraordinary (SX) mods (OSX) perform the maximum mode conversion if the incident wave has an optimal value. Otherwise, the partial conversion takes place where $N_z^2 < 0$. However, this situation can be avoided by using an optimum lurching angle, i.e., $N_{z, \text{opt}} = \sqrt{\frac{Y}{1+Y}}$ where $N_x = N_y = 0$. The condition mentioned will be true when the surface of the cutoff layer is smooth, if not, as depicted in Fig. 2, the incident wave diverges by the plasma turbulence, so, the OSX conversion efficiency is reduces due to the intrinsic change of local refractive index. The less power transmutes to the UHR region, the less overall OSXB conversion efficiency will be obtained. In fact, collisions and scattering cause to damp, weaken and change the direction of OSX. It must be mentioned that although the conversion losses much depend on ω_{ce} , in practice, the magnetic field B and the density gradient $L_n = \frac{n_e}{n_{mc}} \frac{1}{\omega_{ce}}$ play an important role to make the T_{OSXFX} small.

In the hot plasma dispersion and the EBW mode, the values of $\bar{\mu}$ was chosen between 0 and 5 due to flatness of the resonance absorption at low harmonic, nevertheless, the higher harmonic, the higher $\bar{\mu}$ values are needed. Clearly in the mechanism of the collisionless Landau damping phenomena i.e., the wave-particle interaction is raised in the lower harmonic values. This happen, when the electron velocities are too close to the phase velocity of the wave. In Fig. 4, one sees the resonance absorptions of $\frac{\omega_{pe}^2}{\omega_{ce}^2}$ values between 2 and 3 only for the ratios $\frac{\omega_{pe}^2}{\omega_{ce}^2} = 1, 3, 5$. Also, for the values of $\frac{\omega_{pe}^2}{\omega_{ce}^2}$ between 3 and 4, the full resonance absorptions have happened for $\frac{\omega_{pe}^2}{\omega_{ce}^2} = 1, 3, 5, 8, 10$. The latter is also through for the values $\frac{\omega_{pe}^2}{\omega_{ce}^2}$ between 4 and 5, 5–6, and 6–7. It is clear that, as $\frac{\omega_{pe}^2}{\omega_{ce}^2}$ increases, higher harmonies resonance and absorption take place for the higher $\bar{\mu}$, in other words, the higher plasma temperature is, the more microwave penetrates in the plasma center.

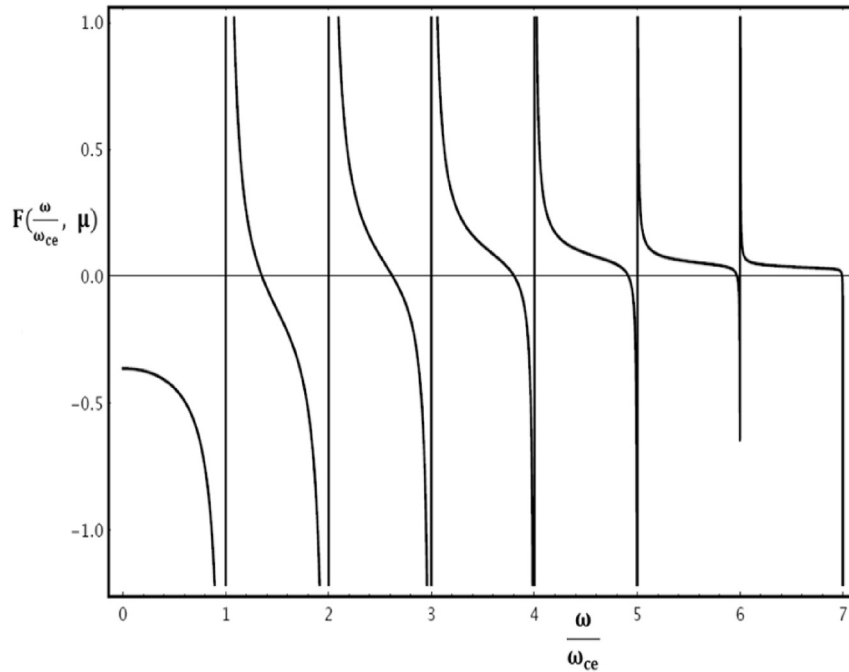


Fig. 5. The Dispersion relation function in terms of $\frac{\omega}{\omega_{ce}}$ for a fixed value of $\bar{\mu}$ ($\bar{\mu} = 2.4$).

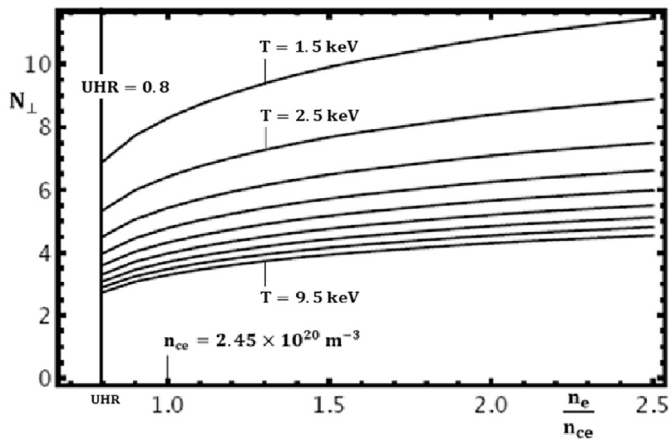


Fig. 6. The perpendicular refractive index as a function of normalized plasma density for the various temperatures at W7X.

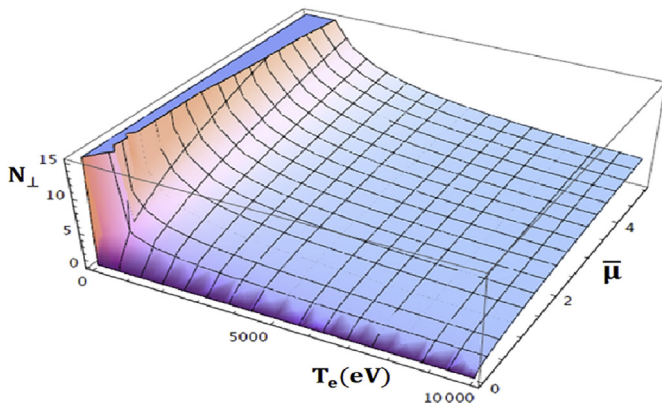


Fig. 7. The perpendicular refractive index versus plasma temperature and $\bar{\mu}$ at W7X.

In Fig. 6, we have displayed the perpendicular refractive index as a function of normalized plasma densities and the various temperatures. As shown, any increment in the plasma temperature causes the perpendicular refractive index to decrease, this effect might be explained as follows; in ECRH, the absorption lines depend on the harmonics and $\frac{\omega_{pe}^2}{\omega_{ce}^2}$ ratios, so, this will be affected by the line absorption broadening due to the Doppler shift when the $\omega = n\omega_{ce} + k_{\parallel}v_{\parallel,e}$ condition is satisfied, where $k_{\parallel}v_{\parallel,e}$ is the Doppler shift, ω is the frequency of externally launched wave, k_{\parallel} is the parallel wave vector and $v_{\parallel,e}$ is the thermal velocity of resonate electrons. In other words, the more plasma is heated, the less is condensed, so, plasma will be more transparent to the wave propagations.

6. Conclusion

The process of OSXB mode conversion heating overdense plasmas on the W7-X stellarator was presented. The formalism of SX mode conversion at UHR to EBW has been considered by taking into account the effect of plasma turbulence on the OSX mode conversion and the losses of FX mode propagation at UHR. Consequently, the overall OSXB conversion efficiency is depend on the launching incident wave at the optimum angle and obviously, on the background magnetic field.

We have shown that a perpendicular propagation, the electrostatic wave, EBW, will be strongly resonantly transfer energy to the electrons at two conditions; a) when $\bar{\mu} \leq 1$ and b) when $\bar{\mu} \gg 1$, and for the right values of $\frac{\omega}{\omega_{ce}}$ ratio. Although we have taken the value of $\frac{\omega}{\omega_{ce}}$ up to 7, higher values have been examined, i.e., up to 10. Moreover, higher harmonics need higher $\bar{\mu}$ value and obviously, higher plasma temperatures with the lower Lamoure radius.

Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.net.2018.06.013>.

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