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ABSORPTION OF ION BERNSTEIN WAVES BY IMPURITY
CYCLOTRON HARMONICS

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ABSTRACT

This paper analyzes the damping of externally-launched ion Bernstein waves by absorption at the cyclotron harmonics of the impurity ions. The inclusion of the non-magnetic energy flux term reduces the damping rate by nearly two orders of magnitude from the previous calculation. Excessive impurity damping can be avoided by launching ion Bernstein waves at a frequency just below the second (or higher) cyclotron harmonic of hydrogen.

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Ion Bernstein wave (IBW) heating is a waveguide-ICRF heating concept for heating large-size fusion plasmas, utilizing a relatively simple, reactor-compatible rf-system [1-3]. The effectiveness of this heating scheme hinges critically on whether or not the waveguide-launched ion Bernstein wave can successfully penetrate deep into the hot dense core of the reactor plasma [2,3]. Ray-tracing calculations in a sheared tokamak geometry have indeed yielded a large accessible window in $n_{\parallel}$ ($n_{\parallel} \leq 7$) which scales very favorably for heating high temperature reactor-grade plasmas [3]. However, calculations by S. Puri (Ref. [1]) would infer that the prospect for excellent wave penetration may be diminished by the presence in the plasma of even a minute amount of impurity ions. As the ion Bernstein wave propagates toward the plasma core, it must traverse numerous ion cyclotron harmonic layers stemming from various ionization states of impurity ions. Strong ion cyclotron harmonic damping on these impurity ions could cause premature absorption of the wave energy and therefore could impede the power flow toward the plasma core. In this note, we include the non-electromagnetic energy flux term in the derivation of the impurity absorption rate and find that the ion Bernstein wave absorption by various impurity ions can, in fact, be made very small.

To calculate the damping, we first compute $\text{Im } k_{\parallel}^*$ due to impurity ions. From Ref. [4] for IBW, one can show that

$$\begin{aligned} \text{Im } k_{\perp}^* &= \text{Im } \epsilon^* / |\partial \epsilon / \partial k_{\perp}| = \text{Im } K_{xx}^* / |\partial K_{xx} / \partial k_{\perp}| \\ &= \frac{\sqrt{\pi}}{|\partial K_{xx} / \partial k_{\perp}|} \frac{\omega_{pi}^*}{\omega k_n V_i} Q_p(\lambda_i^*) \exp \left[- \left(\frac{\omega - p \Omega_i^*}{k_n V_i} \right)^2 \right], \end{aligned} \quad (1)$$

where $\lambda_i \equiv k_{\perp}^2 T_i / m_i \rho_i^2$, K_{xx} is the element of the plasma dielectric tensor, the asterisk denotes impurity ions, $Q_p(\lambda_i^*) \equiv I_p(\lambda_i^*) / \lambda_i^*$, I_p is the modified Bessel function, and p denotes the harmonic number of impurity ions. The contributions from K_{xy} , K_{zz} and n_i^2 terms in Eq. (1) may be neglected here, since in fusion plasmas they are of order m_e/m_i or $n_n^2 \omega^2 / \omega_{pi}^2 \approx 10^{-1} - 10^{-2}$. The damping coefficient $\Gamma_i^* \equiv \int \text{Im } k_{\perp}^* dx$ can now be calculated for the p -th impurity harmonic,

$$\Gamma_{ip}^* = \frac{k_{\perp} R \pi}{(k_{\perp} \partial K_{xx} / \partial k_{\perp})} \left(\frac{\omega_{pi}^*}{\Omega_i^*} \right)^2 Q_p(\lambda_i^*), \quad (2)$$

where R is the magnetic field gradient scale-length, typically equal to the device major radius. It should be noted that the damping Γ_{ip}^* in Eq. (2) is smaller than the one given in Ref. [1] by the factor $2 K_{xx} / (k_{\perp} \partial K_{xx} / \partial k_{\perp}) \approx 2 n_n^2 / \omega_{pi}^2 \approx 10^{-1} - 10^{-2}$, the difference attributable to the omission of the non-magnetic particle energy flux term in Ref. [1] (ISW energy flux is carried mainly by the ion particle motion rather than by the Poynting flux). In deriving Eq. (2), we have neglected the impurity terms in the real part of the wave dispersion relation. This approximation can be shown to be equivalent to

$\Gamma_i^* < k_i R \pi (V_i^* k_n / \omega) \approx 1$. We will see shortly that this condition is usually satisfied where the damping by relatively small impurity concentrations ($\leq$ few percent) is being analyzed.

We now utilize Eq. (2) to investigate the damping by various representative impurity ions. It is reasonably accurate to assume here that $\Gamma_{ip}^* [\approx \lambda_i^{*p-1}/(p-1)!]$ decreases rapidly with decreasing λ_i^* and with increasing harmonic number p . In ion Bernstein wave heating, the wave is launched from the low field region (large R) with relatively small $\lambda_i \leq 0.1$ and propagates toward the plasma core [3]. Due to the increasing magnetic field (or decreasing ω/Ω_i), the wave assumes an increasingly larger λ_i value, which typically reaches $\lambda_i \approx 1$ near the half-way point ($r = a/2$). The absorption therefore tends to be small near the plasma edge, which circumstance minimizes the chance for undesirable edge heating. The absorption rate, noting $\Gamma_{ip}^* = k_i f(\lambda_i) = 1/\rho_i f'(\lambda_i) \propto (T_i)^{1/2}$, also goes down with increasing plasma temperature. Another noteworthy property is the dependence of λ_i^* on the impurity mass m_i^* and charge state Z_i^* : since $\lambda_i^* \propto m_i^*/Z_i^{*2} \propto 1/m_i^* \Omega_i^{*2} \propto p^2/m_i^*$, the λ_i^* value decreases with m_i^* for given p , resulting in very different absorption rates for different impurities. For example, comparing 32-times ionized molybdenum with singly-ionized tritium, both have the same gyro-frequency $\Omega_i^* = \Omega_H/3$, but $\lambda^*(\text{moly}) = \lambda^*(\text{tritium})/32$ (assuming an isothermal plasma) making $\Gamma_{ip}^*(\text{moly}) \ll \Gamma_{ip}^*(\text{tritium})$, which for $p = 5$ yields $\Gamma_{i5}^*(\text{moly}) \approx 10^{-6} \Gamma_{i5}^*(\text{tritium})$, for a given charge concentration. We generally find that increasing p or decreasing λ_i^* causes impurity absorption to go

down rapidly with increasing impurity mass-number and thus, the impurity absorption becomes quite negligible for the high-mass impurities such as tungsten, molybdenum, and niobium. The effect of low-Z impurities, such as carbon, nitrogen, and oxygen, can be expected to be minimized inside hot-dense fusion plasmas where these impurities assume the deuterium-like fully ionized states, eliminating many of the possible cyclotron harmonic resonances. To minimize the damping, it is also advantageous to operate at higher frequencies. For example, by launching an ion Bernstein wave at a frequency just below the second cyclotron harmonic of hydrogen instead of deuterium, one can effectively double the impurity harmonic number p and significantly reduce the damping.

To make a full quantitative assessment of the effect of impurity damping, it is necessary to go to numerical calculations which include the exact wave dispersion relation for realistic plasma and magnetic field profiles. As an illustration, we show in Fig. 1 the absorption rate and corresponding absorption layer position ($R > R_0$) for the dominant impurity harmonics using PLT-parameters for the IBW launched just below the second harmonic hydrogen cyclotron frequency. Each point is labeled according to its harmonic number, impurity, and ionization state; e.g., 50 VI denotes the fifth harmonic of five-times-ionized oxygen. Also in the figure, using a coronal equilibrium model [5], we have indicated with solid dots those impurity states which are likely, and with open circles those states not likely, to exist in a hot fusion

plasma. One sees from the figure that the impurity absorption occurs well inside the plasma core. Moreover, the damping is quite small, $\Gamma_1^* \leq 10^{-3}$, which indicates that ion Bernstein wave heating can tolerate reasonably large impurity concentrations (~10%). Since the number of relevant impurity cyclotron harmonic resonances and their absorption rates generally go down with increasing plasma temperature, the impurity effect should further decrease as one moves toward hotter and cleaner fusion-reactor plasmas. However, the impurity effect may still be important for lower temperature experimental plasmas with high levels of impurities. Calculations also indicate that IBW impurity absorption can be kept small in a D-T reactor plasma by adding a few percent hydrogen and launching the heating wave just below the second-harmonic proton cyclotron frequency.

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FIGURE CAPTION

Fig. 1. Impurity damping coefficient of externally launched second harmonic IBW. $N_i^* Z_i^* = 1\%$, $n_0 = 3 \times 10^{13} \text{ cm}^{-3}$ = 100 n(edge), $T_0 = 1 \text{ keV} = 100 \text{ T(edge)}$, $B_0 = 2.4 \text{ T}$, $R_0 = 130 \text{ cm}$, $a = 40 \text{ cm}$, $R \geq 130 \text{ cm}$, $f = 55 \text{ MHz}$, C-carbon, O-oxygen, N-nitrogen, Ti-titanium, Fe-iron, T-tritium, and D-deuterium.

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Fig. 1