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Non Linear Effects Produced by Electrostatic Waves in a Magnetized Plasma

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Abstract. Some non-linear phenomena, like ponderomotive effects and parametric decays, produced by high power electrostatic waves in a magnetized low density plasma, have been investigated experimentally. The injection of high power electrostatic waves into a plasma causes ponderomotive forces arise. Their action primarily gives rise to a plasma density depletion in front of the launching system and subsequently affects both the wave injection and propagation, producing cavitons.

Beside these effects, RF power produces parametric decays which are also responsible of an edge electron heating.

Above mentioned phenomena were studied in the range of low frequencies ($1 \div 100$ MHz), in conditions of high ($n_e \approx 10^{11} \text{ cm}^{-3}$) and low ($n_e \approx 10^9 \text{ cm}^{-3}$) density, analyzing the modifications of the electron density and temperature profiles, the shape of e.s. waves's electric field and the spectrum of the detected signals.

1. GENERAL DEDUCTION OF A PONDEROMOTIVE FORCE DENSITY

To interpret accurately the ponderomotive effects, it is necessary to include the ponderomotive force in the fluid description of plasmas by calculating the generalized force density term $\nabla \cdot (nm\underline{v}\underline{v})$ in a non-collisional momentum balance equation

$$\frac{\partial}{\partial t}(nm\underline{v}) + \nabla \cdot (nm\underline{v}\underline{v}) + \nabla \cdot \underline{\underline{p}} + ne\left(\underline{E} + \frac{1}{c}\underline{v} \times \underline{B}\right) = 0 \quad (1)$$

and defining

$$\underline{F}_{\text{PM}} = \frac{1}{n(\underline{r})} \underline{f}_{\text{PM}}(\underline{r}) = \frac{-1}{n(\underline{r})} \langle \nabla \cdot nm\underline{v}\underline{v} \rangle_T = -\nabla V_{\text{PM}} \quad (2)$$

where $n(\underline{r})$ is the particle number density and $\langle \dots \rangle_T$ is the average value in an oscillation period of the particle motion.

One obtains, in slab geometry:

$$\underline{f}_{\text{PM}} = -\frac{1}{8\pi} \sum_s \left\{ \hat{x} \left[\frac{\partial}{\partial x} \left(\frac{\omega_{ps}^2 \omega^2}{(\omega^2 - \Omega_s^2)^2} E_{\perp}^2 \right) + \frac{\partial}{\partial z} \left(\frac{\omega_{ps}^2}{\omega^2 - \Omega_s^2} E_{\perp} E_{\parallel} \right) \right] + \hat{z} \left[\frac{\partial}{\partial x} \left(\frac{\omega_{ps}^2}{\omega^2 - \Omega_s^2} E_{\perp} E_{\parallel} \right) + \frac{\partial}{\partial z} \left(\frac{\omega_{ps}^2}{\omega^2} E_{\parallel}^2 \right) \right] \right\} \quad (3)$$

where ω_{ps} and Ω_s are the plasma and the cyclotron frequencies of that species of particles.

In the WKB approximation, one can simplify eq.3 by expressing the derivatives of the electric field intensity, obtaining a general form of the ponderomotive force density that include terms which take into account the ion dynamics and forces due to density gradients:

$$\underline{f}_{\text{PM}} = -\frac{1}{8\pi} \sum_s \left\{ \hat{x} \frac{\partial}{\partial x} \left[\left(\frac{\omega_{ps} \omega}{\omega^2 - \Omega_s^2} \right)^2 E_{\perp}^2 + \frac{\omega_{ps}^2}{\omega^2 - \Omega_s^2} E_{\parallel}^2 \right] + \hat{z} \frac{\partial}{\partial z} \left[\frac{\omega_{ps}^2}{\omega^2} E_{\parallel}^2 + \frac{\omega_{ps}^2}{\omega^2 - \Omega_s^2} E_{\perp}^2 \right] \right\} \quad (4)$$

Eq.4 introduces ponderomotive effects due to density gradients through the derivatives of ω_{ps} .

If $\underline{f}_{\text{PM}}$ is the ponderomotive force density on the plasma fluid, the ponderomotive potential V_{PM} is its integral in space. To write down a simple form of V_{PM} we shall consider high frequencies. Far from the resonance with Ω_s (this means $\omega \gg \Omega_s$) one can simply write:

$$V_{\text{PM}} = \sum_s \frac{1}{n_s} \frac{\omega_{ps}^2}{\omega^2} \frac{E^2}{8\pi} = \sum_s \frac{e^2 E^2}{2m_s \omega^2} \quad (5)$$

In both the IBW and the EPW regimes, near the lower hybrid resonance, the perpendicular wave electric field dominates the parallel one ($E_{\perp} \gg E_{\parallel}$) because of the fact that $k_{\perp} \gg k_{\parallel}$ ($E_{\perp}/E_{\parallel} = k_{\perp}/k_{\parallel} \approx 10^2$). The ponderomotive force can be then approximated neglecting the z component in eq.4 and considering only the term depending on $E_{\perp}$. It turns out that the ponderomotive force acts perpendicularly to the magnetic field, pushing, in front of the antennas, the plasma edge to the inside:

$$\underline{f}_{\text{PM}} = \hat{x} \frac{\partial}{\partial x} \left(\frac{\omega_{pi}^2 \omega^2}{(\omega^2 - \Omega_i^2)^2} \frac{E_{\perp}^2}{4\pi} \right), \quad (6)$$

where we neglected all electronic terms because of the low density values in our experiment. In fact to match the ionic terms of eq.6, ω_{pe}^2/ω^2 (eq.4) has to grow to about 10^4 . At relatively high densities (about 10^{10} cm^{-3}) the parallel action of the ponderomotive forces, mainly supported by electrons, again becomes significant and comparable to the perpendicular ionic term.

2. EXPERIMENTAL RESULTS

The experiment is performed on the *Thorello* device which has the following parameters: major radius $R = 40$ cm , minor radius $a = 8$ cm , toroidal magnetic field $B_o = 2.3$ kG , plasma density $n = 10^8 \div 10^{11}$ cm⁻³ , electron temperature $T_e = 1 \div 10$ eV , ion temperature $T_i = 0.1 \div 1$ eV . Previous theoretical considerations support our experimental results in so far the ponderomotive effect we revealed grows with wave power, which is proportional to E^2 and acts perpendicularly to the toroidal magnetic field as can be deduced from the density growth in the inner plasma. The plot of the experimental density value as a function of the applied power (fig.1) shows an exponential edge density decrease with power. Same behaviour was observed at different toroidal locations. The effect mostly appears before the layer where the conversion from a lower hybrid wave (LHW) to an ion Bernstein wave (IBW) takes place.

A Boltzmann balance equation permits to establish the way in which the electron density n_e is affected by ponderomotive effects:

$$\frac{n_e}{n_{oe}} = e^{-V_{PM}/T_e} \quad , \quad (7)$$

where n_{oe} is the electron density in absence of RF and T_e the electron temperature. The ponderomotive effect becomes relevant whenever its potential matches the thermodynamical energy of the electrons, i.e. when V_{PM}/T_e gets close to 1. Such an exponential behaviour can be observed in fig.1 up to a wave power of $P \approx 400$ mW while for higher power values the density results independent from injected power. This phenomenon is due to the electron heating effects (fig.1) that make the threshold value for ponderomotive effects increase.

The fact we did not observe any significant dependence of the ponderomotive force on the launched $k_{||}$ value (fig.2) confirms our hypothesis that the parallel term in eq.4 (containing $k_{||}$ from the z derivatives of the electric field) is negligible compared to the perpendicular one.

In what concerns the wave modification, we could observe how the wave envelope changed its

shape while the RF-power is increased. At high power levels, the wave energy is highest where the plasma density is mostly depleted. This means that the wave is trapped in the cavity formed by ponderomotive forces and that it does not propagate to the plasma inner.

fig.1: Dependency of electron density and electron temperature from the injected wave power for $f = 6$ MHz , $B_o = 2$ kG

At high frequencies the ponderomotive effect becomes less remarkable while another non-linear phenomenon arises, especially in experiments performed on a plasma of higher density. Fig.3 shows parametric decay instabilities occurring for a frequency of $f = 80$ MHz mainly at the plasma edge: the lower hybrid pump wave decays there into other lower hybrid waves and into ion cyclotron quasi modes. The frequencies for which this instability could be observed were in the range of $\omega \approx 20 \Omega_i$; the ion cyclotron modes are characterized by frequency values near the ion cyclotron frequency ($\omega \approx \Omega_i$).

fig.2: Density profiles for two values of parallel wavevector component for $f = 6$ MHz:
 $\circ$: $k_{\parallel} = 0,001 \text{ cm}^{-1}$, $\bullet$: $k_{\parallel} = 0,11 \text{ cm}^{-1}$

The parametric decays produce a strong plasma heating at the edge so that the threshold for ponderomotive effects becomes so high that the density depletion is not observable anymore.

fig.3: RF signal spectrum obtained for $f = 80$ MHz, $n_e = 10^{10} \text{ cm}^{-3}$, $T_e = 1 \text{ eV}$, $B_o = 2 \text{ kG}$

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