Whistler wave dispersion measurements near the ion gyro frequency

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Investigation of ion whistler waves under laboratory conditions is difficult because of the long wavelength. In the VINETA device electromagnetic waves around the ion gyro frequency have been successfully launched. For frequencies above the ion gyro frequency the waves are identified as R-waves. Below the ion gyro frequency the measurements cannot be explained by R-wave or L-wave dispersion alone. In a heuristic way the observed dispersion is described by the difference wavelength of R-wave and L-wave.

1. Introduction

Whistler waves have been subject of research for almost one century [1]. Excited by lightning whistler waves, low frequency electromagnetic plasma waves, are known to propagate in the ionosphere along magnetic field lines. Because of their dispersion, high frequencies propagate faster then low frequencies and therefore, whistling tone bursts of descending frequency can be observed. Ion whistler waves, with a different dispersion behaviour, were observed by satellites [2]. But until today, there was no observation of L-waves in laboratory plasmas.

Waves in magnetised plasmas can be distinguished in wave propagation parallel and perpendicular to the ambient magnetic field. Whistler waves are of the type $k \parallel B_0$. Starting with a cold plasma dispersion relation, an expression for waves with $k \parallel B_0$ such as

$$\frac{k_{\parallel}^2 c^2}{\omega^2} = 1 - \frac{\omega_{pe}^2 + \omega_{pi}^2}{(\omega \pm \omega_{ci})(\omega \mp \omega_{ce})} \quad (1)$$

is found [3]. Here $\omega_{ps}^2 = (n_e q_s^2 / m_s \epsilon_0)$ is the plasma frequency and $\omega_{cs} = |q_s| B_0 / m_s$ the gyro frequency of the species s. The dispersion relation contains two different modes, where the first (upper choice of signs) is the R-wave and the second (lower choice) is the L-wave. The ion gyro frequency represents a resonance for L-waves, and the propagation is limited to frequencies below this resonance. Waves propagating in this regime are called ion whistler waves.

In multicomponent plasmas a separate resonance occurs for each ion species. The frequency regime of propagation depends on the ion species as well as on the relative ion concentrations. At a certain frequency between two neighbouring ion gyro frequencies the dispersion of R-wave and L-wave intersect. A mode coupling of R-mode to L-mode can occur at this crossover frequency [4]. Measurements of the dispersion behaviour provides a diagnostic tool for ion concentrations as as well for plasma composition. This diagnostic tool has already been used to determine ionospheric plasma composition, but the observations partially deviate from standard models [5]. Laboratory measurements could be helpful to clarify this.

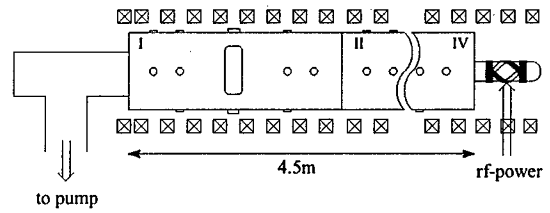

Figure 1: Schematic diagram of the VINETA device. The device consists of four identical modules (I-IV). Only one complete module is shown in the schematic (module I). On the l.h.s. the vacuum pump is indicated and the helicon source is located on the r.h.s.

2. Experimental Setup

Experiments were carried out in the linear VINETA device [6], plotted in Figure 1. The vacuum chamber is made up of four identical modules of 0.4 m in diameter and 1.1 m in length and is immersed in a set of 36 magnetic field coils ($B_0 \leq 100\,\mathrm{mT}$). The plasma source (a right hand half-turn helical antenna) is placed at one end of the device. The antenna is driven with rf of $5-30\,\mathrm{MHz}$ and power of up to 2.5 kW in cw-mode and 6 kW in pulsed mode. Depending on gas pressure, magnetic field strength and power, three different discharge modes can be established (capacitive, inductive, and helicon mode). Plasma densities are in the range of $10^{16} - 10^{19}\,\mathrm{m}^{-3}$ and electron temperature in the range $1 - 5\,\mathrm{eV}$.

Whistler waves are launched by a loop antenna with 30 mm in diameter [7]. The antenna is placed centrally in the device and its surface normal is oriented parallel to the ambient magnetic field. In order to induce a magnetic field perturbation $\delta B / B_0$ in the range of a few percent, the exciter signal power is in the order of $P = 50\,\mathrm{W}$. The waves are detected by magnetic fluctuation probes ($\dot{B}$-probe) [8]. As the induced voltage at the probe is proportional to the exciter frequency ($U_{ind} \propto \omega$), the probe consists of 25 windings 25 mm in diameter to provide a sufficient sensitivity. A computer controlled high-resolution probe positioning system is used for two-dimensional (radial-axial) measurements of propagating wave fronts. Helium is used as filling gas with typical gas pressure of $0.2 - 3\,\mathrm{Pa}$.

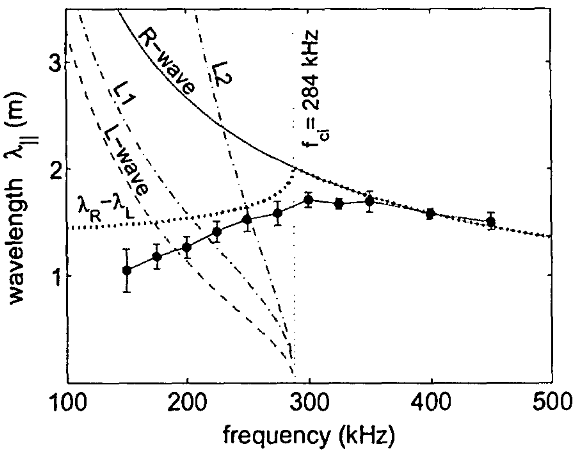

Figure 2: Measurements of whistler wave dispersion (markers). The calculated dispersion relations of an R-wave (solid line) and L-wave (dashed line) are shown as well. Superpositions of R- and L-waves ($L1, L2 = 2\pi/(k_L \pm k_R)$) are represented by dash-dotted lines and the dotted line is the difference wavelength ($\lambda_R - \lambda_L$).

3. Results and Discussion

The experiments were done in a helium helicon discharge operated at a neutral gas pressure of $p = 2.5\,\mathrm{Pa}$, magnetic field of $B_0 = 75\,\mathrm{mT}$ and rf power of $P_{\mathrm{rf}} = 5\,\mathrm{kW}$. The plasma parameters are found to be $n \approx 4 \cdot 10^{18}\,\mathrm{m}^{-3}$ and $T_e \approx 5\,\mathrm{eV}$ from Langmuir probe characteristics. The experimental results for exciter frequencies in the range $100 - 500\,\mathrm{kHz}$ are shown in Figure 2 (markers). The obtained wavelengths are in the range of $1 - 2\,\mathrm{m}$. The increase of the errorbars at small frequencies is related to decreasing sensitivity of $\dot{B}$-probes. For frequencies above the ion gyro frequency $f_{ci} = 284\,\mathrm{kHz}$, the measured wavelengths decrease with increasing frequency. These part of the dispersion has been identified as the R-wave dispersion in a previous measurement [6]. The present measurements agree very well with the calculated dispersion (solid line). Below the ion gyro frequency the observed wavelengths decrease with decreasing frequency. This behaviour can neither be described by R-wave (solid line) nor by L-wave (dashed line) dispersion. Since the antenna does not prescribe a polarisation direction, both R- and L-waves are excited simultaneously. Similarly the $\dot{B}$-probe measurement is sensitive to magnetic fluctuations only, hence different circular polarisations cannot be distinguished. Wavelengths (L1,L2) calculated from linear superposition of R-wave and L-wave cannot explain the measurements below f_{ci}. $L1 = 2\pi/(k_L + k_R)$ and $L2 = 2\pi/(k_L - k_R)$ are plotted dash-dotted in Figure 2. Especially, no discontinuous jump is observed around f_{ci}. Nevertheless, the deviation form the R-wave dispersion below f_{ci} indicates that the L-wave is involved as well. Possibly, a non linear superposition of R- and L-wave necessary to explain the measurements (maybe due to the high excitation power used). A more appropriate (heuristic) agreement is to the difference wavelength $\lambda_R - \lambda_L$ (dotted line). This will be analysed in future investigations. To our knowledge, this is the first experimental observation of L-wave propagation under laboratory conditions.

4. Summary and Conclusion

Waves has been launched with frequencies near the ion gyro frequency. For frequencies above the ion gyro frequency, a decreasing wavelength with increasing frequency is observed. This behaviour is very well described by an R-wave dispersion. Below the ion gyro frequency a decreasing wavelength is observed for decreasing frequencies. Neither R-wave, L-wave dispersion nor a linear superposition of both can explain these measurements. A more reasonable approach, but so far only heuristic, is given by the difference wavelength of R-wave and L-wave.

Acknowledgement

This work was performed under the auspices of DFG Sonderforschungsbereich 198 "Kinetics of ionized plasmas" Greifswald-Rostock project A15.

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