Propagation of Electrostatic Waves near the Lower Hybrid Frequency in a Toroidal Plasma, NOVA-I

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Abstract

Resonance cones in a lower hybrid range of frequency are observed and confirmed under the combined influence of toroidicity and inhomogenity in a toroidal device NOVA-I.

The resonance cone is investigated in two different plasma sources, i.e. (A) a steady plasma of low density ($N_e \sim 5 \times 10^9$ cm^{-3}), and (B) a pulsed tokamak plasma of high density ($N_e \sim 2 \times 10^{13}$ cm^{-3}). In case (A), the experimental results agree well with the trajectories computed from a simple cold plasma dispersion relation. Even in the high density tokamak plasma of case (B), a wave penetration toward the plasma center is observed and its behavior also agrees qualitatively with the thoery.

Introduction

Plasma heating near the lower hybrid frequency has become important as a possible means of the further heating in the thermonuclear fusion research. Externally excited lower hybrid waves, if an accessibility condition is satisfied, can propagate toward the resonance layer along conical surfaces, called resonance cones.

An existence of resonance cones in a homogeneous cold plasma was first discussed by Bunkin[1] and Kuehl[2], and was experimentally measured by Fisher and Gould.[3] They have shown that fields of waves excited by a dipole antenna have a singularity on the surface of a cone with its axis parallel to the magnetic field, and the group velocity tends to zero on the surface. In an inhomogeneous plasma, Briggs and Parker[4] have observed that the singularity of the potential of electrostatic waves, excited by a localized coupling structure, appears on the curved surface of a cone, and that the wave energy is transported to the lower hybrid resonance layer along the locus of the singularity. The effects of finite-sized RF sources on the wave pattern within the resonance cones have been numerically investigated by Bellan and Porkolab.[5] In a

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toroidal plasma, Javel et al. have investigated experimentally the resonance cones of plasma waves.[6] More recently, in a bounded cold inhomogeneous cylindrical plasma, the propagation of the lower hybrid waves, excited by an arbitrary sized electrostatic coupler, has been numerically studied by Colestock and Getty.[7]

A remaining important problem to be solved is an investigation of the propagation of lower hybrid waves in a tokamak geometry. Numerically it has been shown that the trajectory of a wave energy flow rotates in a spiral form around the magnetic axis due to a poloidal magnetic field, and then reaches the lower hybrid resonance layer.[8),9),10]

In this paper we investigate the propagation of electrostatic waves in a toroidal device NOVA-I. Experiments are carried out in two different plasma sources. In the first case (A), a steady state and relatively low density plasma ($N_e \sim 5\times10^9$ cm^{-3}) is used. In the second case (B), we use a higher density tokamak plasma ($N_e \sim 2\times10^{13}$ cm^{-3}).

Experimental Apparatus and Measurements

The experiments are carried out in a small tokamak NOVA-I[11], having a major radius $R=18$ cm and a minor radius $a=2.5$ cm (shown in Fig. 1). The discharge chamber is made of pyrex glass with an inner radius of 3.0 cm. The working gas is argon at pressures of 2.8×10^{-4} torr. Two different plasma sources are used. In case A, the plasma is steadily produced by a cw 25 MHz, 100 W RF generator which is capacitatively coupled to the plasma by means of two band electrodes of 3.5 cm diameter and 1.5 cm width. Typically, the electron density is about 5×10^9 cm^{-3} and the electron temperature 7 eV, which are measured by a double probe. The toroidal magnetic field

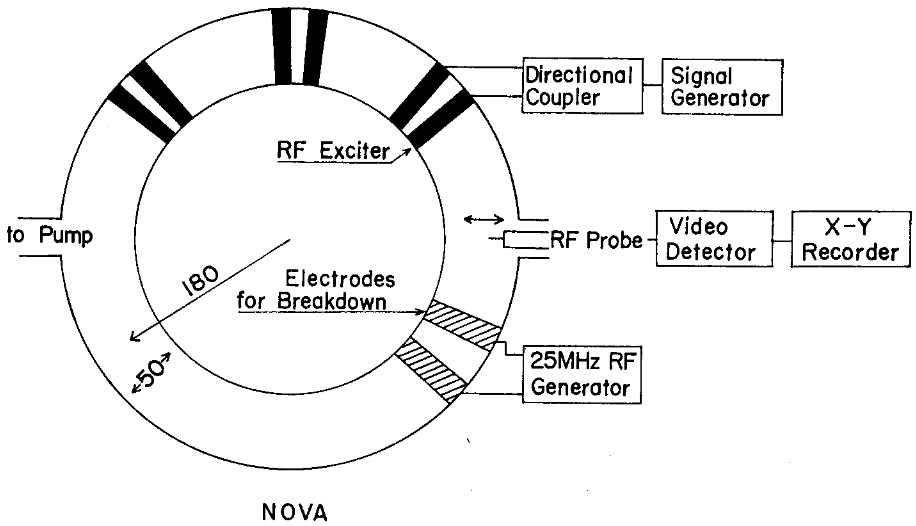

Fig. 1. Schematic diagram of the experimental apparatus.

is 400 G. and there is no plasma current. In case B, a tokamak plasma is used. Its main parameters are as follows: the electron density and temperature are 2×10^{13} cm^{-3} and 10 eV, respectively. The maximum plasma current is about 1 kA and the discharge lasts 2 msec. The toroidal magnetic field is 4.75 kG.

Five pairs of two ring-electrodes, which are wound tightly around the chamber, are used to investigate the wave propagation. The width of a ring is 1 cm and the interval of two rings is also 1 cm. Five pairs of ring-exciters are placed at intervals of 7 cm respectively. RF signals are fed into two rings in the opposite phase, so that the direction of the RF electric field is parallel to the toroidal magnetic field. A movable co-axial probe is used to measure the RF potential in a plasma. The diameters of the inner and outer conductors are 0.5 mm and 1.5 mm respectively, and the receiving tip is 5 mm length. We measure the radial (X) or vertical (Y) distribution of the RF potential in the plasma as a function of the toroidal distance (Z) between the probe and the exciters.

Experimental Results and Discussions

(1) Case A (Low Density Case)

The plasma density profile measured by a double probe is shown in Fig. 2 (a). Figure 2(b) shows the radial profiles of the RF potential at various axial distances (Z) between the probe and the exciter. One can see the two peaks of the RF potential, which are regarded as the resonance cone surfaces. In this case, the incident frequency was chosen to be 40 MHz. The lower hybrid resonance frequency calculated from the peak density and the magnetic field is about 2 MHz. Figure 2(c) shows the resonance cone trajectories of waves emanating from an exciter which is located at $Z=0$ and $X=\pm3.0$ cm. The open circles indicate the observed maximum potential, and the solid lines indicate the resonance cone trajectory which is described by the following equation,

$$Z=1.5-\int_{X_p}^{X} dX\sqrt{-\frac{K_\perp(X)}{K_{\parallel}(X)}} \tag{1}$$

where $X_p=\pm3.0$ cm represents the plasma edges, and $K_\perp=1-\frac{\omega_{pi}^2}{\omega^2}+\frac{\omega_{pe}^2}{\omega_{ce}^2}$ and $K_{\parallel}=1-\frac{\omega_{pe}^2}{\omega^2}$ are elements of the cold plasma dielectric tensor **K**. The agreement between the experiments and the calculations is quite satisfactory.

In order to study the spiral trajectory of the wave energy flow in tokamak plasma, three pairs of two arc-shaped exciters with a 2 cm length and a 1 cm width are also used for azimuthally localized exciters. The RF signal is also fed into two arc-shaped exciters in the opposite phase. The radial profiles of the wave potential at driving frequencies of 40 to 110 MHz for a fixed interval between the probe and the exciter are shown in Fig. 3(a). In this case, the exciter is located at $X=+3.0$ cm, so that only

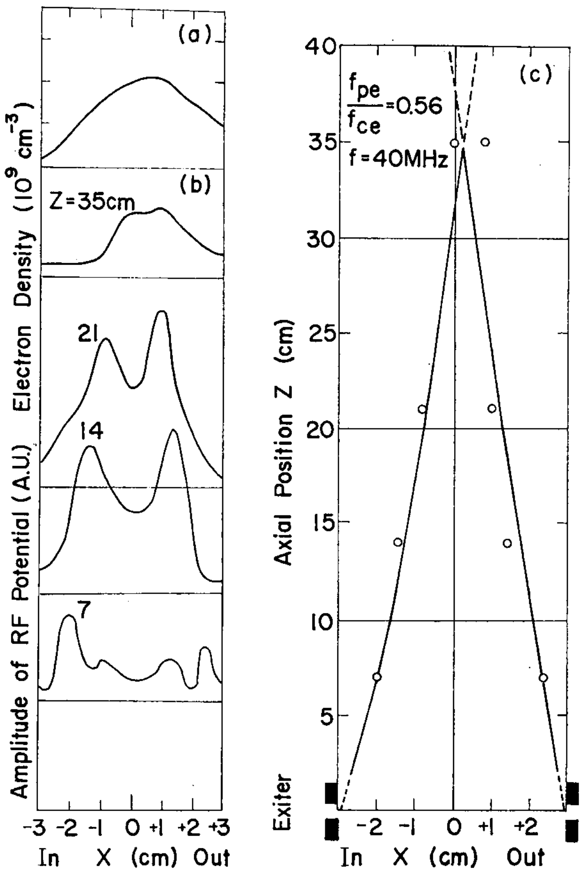

Fig. 2.

(a) The electron density profile along the major radius (N_{e0}~5×10^9 cm^{-3})

(b) Observed RF potential profiles for various distances between the fixed probe and the exciter. ($f_{pe}/f_{ce}=0.6$, $f=40$ MHz, $f_{LHO}=2$ MHz.)

(c) The trajectories of waves launched from a exciter at $X=\pm3.0$ cm and $Z=0$. Solid lines, the ray trajectories calculated from the density profile (Fig. 2(a)); and open circles, the position of the observed maximum potential.

one peak is observed. The position of the peak shifts radially inwards through increasing the frequency at a fixed toroidal position. According to the theory of the resonance cone,[3] the cone angle becomes larger through increasing the frequency. The experimental results agree qualitatively with the theoretical behavior. The relations between the radial location of the cone and the frequencies are shown in Fig. 3(b). Three lines for each Z-value are computed from Eq. (1) for the various values of the peak density N_{e0} (i.e. 3, 4, and 5×10^9 cm^{-3}).

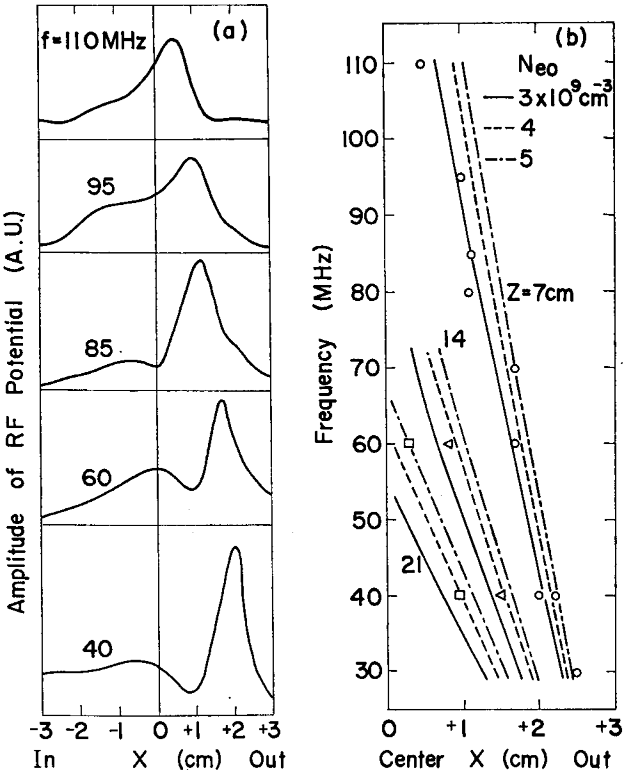

Fig. 3.

(a) Observed RF potential profiles for various incident frequencies at a fixed toroidal distance $Z=7$ cm. ($f_{pe}/f_{ce}=0.6$, $f_{\mathrm{LHO}}=2$ MHz.)

(b) Relation between the position of the RF potential peak and the incident frequency. Three lines for each toroidal distance $Z=7$, 14 and 21 cm, indicate the calculated value from the measured density profile (Fig. 2(a)) for various values of the peak density $N_{e0}=3$, 4 and $5\times10^{9}\,\mathrm{cm}^{-3}$.

(2) Case B (High Density Case)

In a tokamak discharge, the feature of the propagation of static waves seems to be different from case (A). The effects of the poloidal magnetic field due to the plasma current ($I_p=1$ kA) can be neglected because the toroidal field is stronger than it. Because of the plasma current, however, the fluctuation of the plasma density becomes larger and the density gradient near the limiter ($a=2.5$ cm) becomes steeper. These facts seem to prevent the waves from propagating smoothly along the resonance cone trajectory.

The discharge lasts about 2 msec and the plasma density during the discharge changes up to $2\times10^{13}\,\mathrm{cm}^{-3}$. Three pairs of two ring-exciters are also used to invest-

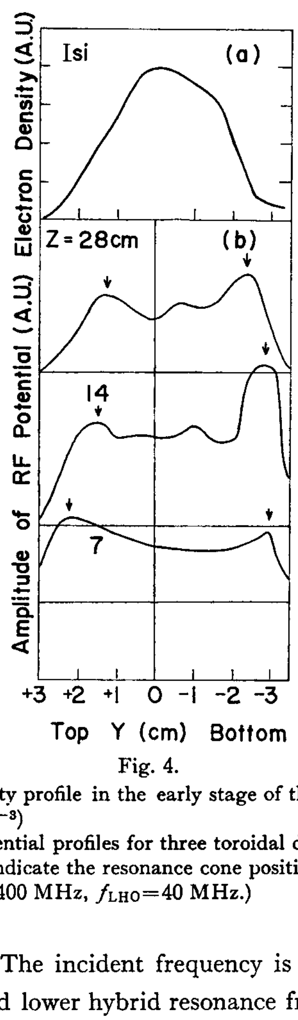

Fig. 4.

(a) The vertical density profile in the early stage of the tokamak discharge. ($N_{e0}=7\times10^{12}\,\mathrm{cm}^{-3}$)

(b) Observed RF potential profiles for three toroidal distances $Z=7$, 14 and 28 cm. Arrows indicate the resonance cone position. ($f_{pe}/f_{ce}=1.5$, $f=400$ MHz, $f_{LHO}=40$ MHz.)

igate the wave propagation. The incident frequency is 400 MHz which is about ten times as high as the calculated lower hybrid resonance frequency (~40 MHz for Ar^+). The vertical profiles of the plasma density and the wave potential are measured shot by shot in every discharge.

The feature of the wave penetration varied as the density changed in the discharge. In the early stage of the discharge ($N_e\sim5$–$7\times10^{12}\,\mathrm{cm}^{-3}$), a concentration of the wave energy in the plasma was observed and the propagation of static waves was confirmed. Figure 4(b) shows the vertical wave potential profiles at toroidal distances $Z=7$, 14 and 28 cm, respectively. The position of arrows in the figure is regarded as resonance surfaces. This result is quite similar to the feature of the RF potential distribution in case A, but does not quantitatively agree with the trajectory calculated from the measured density profile (shown in Fig. 4(a)). This discrepancy is probably due to the strong modification of the density profile by the insertion of the probe. In the middle stage of the discharge ($N_e\sim2\times10^{13}\,\mathrm{cm}^{-3}$), the position of the peak of the wave potential did not change. That is, waves can not propagate into the interior region of the plasma and stay at the position of the limiter ($a=\pm 2.5$ cm). This may be attributed to the change of the coupling to the plasma due to the increased density and the sharp density gradient near the exciter. At the end of the discharge ($N_e < 5\times 10^{12}$ cm^{-3}), a highly concentration of wave energy was again observed. Waves can propagate toward the center of the plasma column through decreasing the density.

Summary

We have investigated the wave propagation in toroidal plasma. A high concentration of RF power in the direction along the density gradient has been confirmed. In a steady low density plasma, the experimental results of trajectories of wave energy agree very well with the values calculated from the measured density profile by taking into account the toroidicity. Even in a higher density tokamak plasma, we have shown that static waves travel along a resonance cone in the early stage of the discharge, having a relatively low density.

Ackowlegements

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