Characteristics of the Cyclotron Harmonic Resonances found by Impedance Probe Experiments in a Laboratory Plasma

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The RF impedance of an antenna in a thermal magnetized plasma shows resonances associated with the electron cyclotron harmonic frequency. To understand the impedance probe observations in the thermal anisotropic plasma, characteristics of the cyclotron harmonic resonances have been examined. We verified that both the series and parallel types of the resonances occurred in a laboratory experiment. The resonance effect became clear when the static magnetic field was nearly parallel to the cylindrical probe axis. In this case the cyclotron harmonic resonances would act to smear the upper hybrid resonance, the measurement of which is essential to know the electron density. It was also found that the 2nd order of the cyclotron harmonic series resonance sometimes became much clearer than the plasma sheath resonance which is a main series resonance in the cold plasma. The ion sheath surrounding the probe probably played a significant role to produce such unique resonance characteristics in the thermal plasma.

Keywords: impedance probe, resonance, electrostatic electron cyclotron wave, ion sheath, plasma diagnostics

1. Introduction

The impedance probe is a powerful tool for measuring the absolute electron number density in a plasma. The frequency spectrum of the probe RF impedance enables us to determine the electron density accurately by detecting the upper hybrid resonance (UHR) frequency. Many researchers have applied the impedance probe to both the space and the laboratory plasma diagnostics for more than half a century [1-5].

Although the measurement principle of the impedance probe technique is based on the theory of the impedance of an antenna in a cold plasma, some experimental results showed that the probe impedance was affected by thermal electrons. The probe self-impedance observed by sounding rocket experiments showed distinctive changes near the 2nd harmonics of the electron cyclotron frequency [6,7]. Mutual impedance probe measurements also found impedance variations at the cyclotron harmonic frequencies and the resonance frequencies of the Bernstein waves so-called f_Q [8-10]. In an extreme case, the GEOS-1 satellite observed a harmonic structure of the mutual-impedance at up to 16th harmonics of the cyclotron frequency [8]. Ejiri [11] confirmed that excited plasma waves from the mutual impedance probe satisfied the Bernstein mode dispersion relation by a laboratory experiment. These phenomena relating to the harmonics of the cyclotron frequency are attributed to the kinetic effect of thermal plasma as demonstrated by Bernstein [12].

It is important to clarify the resonance characteristics of impedance probe in the thermal magnetized plasma. Appearance of the cyclotron harmonic resonance near the UHR frequency reduces the accuracy in the electron density measurements [6]. Particularly, an automatic UHR detection type of the impedance probe [13] will fail to find the UHR frequency unless we figure out the resonance features.

The impedance of an antenna in a thermal magnetized plasma is a fundamental issue of the plasma physics. As represented by Balmain's pioneering work [14], many authors have investigated the antenna impedance by applying the cold plasma approximation; and there have been few attempts that the antenna impedance has been treated by the kinetic theory. Theoretical evaluations of the antenna impedance in the thermal plasma were applicable in limited models [15-17]. Simulation researches have made progress in recent years [18,19], however, there were no published papers which concerned the cyclotron harmonic resonances to the best of our knowledge.

The main objective of this study is thus analyzing the effects of the electrostatic electron cyclotron waves on impedance probe measurements. Note that Crawford *et al.* already ascertained the existence of the cyclotron harmonic resonances [15,16]. We clarified here what kind of

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condition gave rise to the distinct cyclotron harmonic resonances by performing laboratory experiments. It will be applicable to interpret impedance observations in the ionospheric plasma. A unique property of the resonance, which was most likely to be affected by the ion sheath, was also reported.

2. Theory

As demonstrated in the earlier study [16], the perpendicular component of the permittivity tensor $\varepsilon_\perp$ provides knowledge of resonance frequencies. The normalized equivalent capacitance of a cylindrical probe, whose axis is parallel to the static magnetic field, is proportional to the perpendicular permittivity. The absolute permittivity takes minimums at the parallel resonance frequencies and maximums at the series resonance frequencies.

The perpendicular permittivity of the cold electron plasma is given by

$$\varepsilon_\perp = 1 - f_p^2 (f - if_v) \Big/ \left[f(f - if_v)^2 - f_c^2 f \right], \qquad (1)$$

where f_c is the electron cyclotron frequency, f_p is the electron plasma frequency, and f_v is the collision frequency. In a case the electron temperature is not negligible, the permittivity of Maxwellian plasma is

$$\begin{aligned} \varepsilon_\perp &= 1 - 2(f - if_v) f_p^2 \exp(-\lambda) / (f_c^2 f \lambda) \\ &\times \sum_{n=1}^{\infty} I_n(\lambda) / \left[(f - if_v)^2 / (nf_c)^2 - 1 \right], \end{aligned} \qquad (2)$$

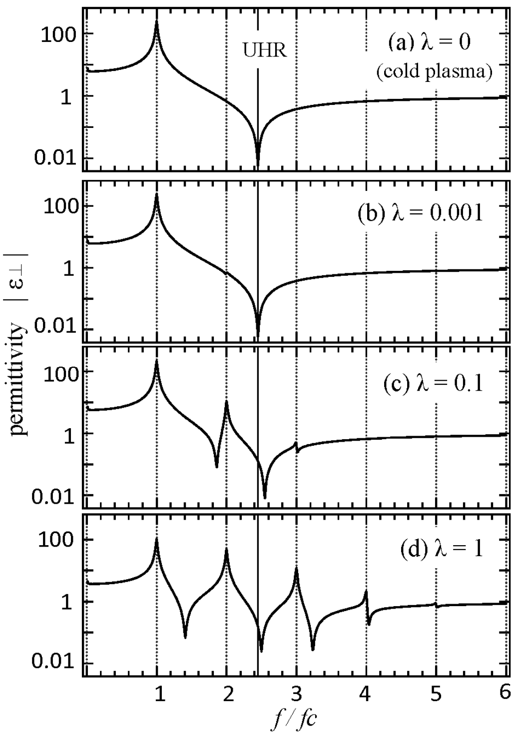

Fig.1 The perpendicular permittivity. (a) cold plasma case. (b)-(d) thermal plasma case. Characteristic frequencies are f_c=1.00 MHz, f_p=2.24 MHz, and f_v=0.01 MHz.

where $\lambda = (k_\perp R_L)^2$, $k_\perp$ is the perpendicular wave number, and R_L is the electron Larmor radius as a function of the electron temperature [15,20].

Figure 1 (a) shows the perpendicular permittivity of the cold plasma. There is a parallel resonance at UHR frequency, which makes it possible to measure the electron density. The absolute permittivity takes a maximum value at the cyclotron frequency. In actual condition, the capacitance of an ion sheath around the probe shifts series resonance frequencies. As a result, the series resonance which is called the plasma sheath resonance (SHR) appears at the higher frequency than the cyclotron frequency [21,22]. On the other hand, the parallel resonance frequency is independent of the ion sheath.

In the case of the thermal magneto-plasma as indicated in Fig. 1 (b)-(d), we can find additional resonances. The series resonances exist at the harmonics of the cyclotron frequency. There are also parallel resonances between each cyclotron harmonics. It should be mentioned that the Bernstein mode waves satisfy the dispersion relation at these parallel resonance frequencies. Figure 1 indicates that increasing λ creates a distinctive signature of the cyclotron harmonic resonances. It should be also noted that the parallel resonance frequency varies from the UHR frequency in a case of large λ.

3. Experiments

3.1 Instruments

A schematic diagram of the impedance probe is shown in Fig. 2. The dimensions of the cylindrical sensor were 77 cm in length by 6 mm in radius. The impedance bridge was properly adjusted to eliminate errors caused by the stray capacitance in the electric circuit. The output signal was the probe equivalent capacitance $C(\omega)$

$$C(\omega) = \left| 1 / i\omega Z(\omega) \right|, \qquad (3)$$

where Z is the probe self-impedance. This system was designed to measure the probe equivalent capacitance in a frequency range of 0.3-10.3 MHz.

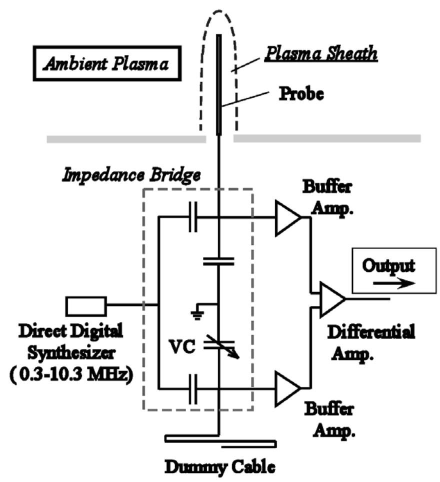

Fig.2 Block diagram of the impedance probe.

The impedance probe experiments were carried out in the large Space Plasma Simulation Chamber at the Institute of Space and Astronautical Science (ISAS). The length and diameter of the chamber are 5.0 m and 2.5 m, respectively. The back diffusion type plasma source ionized an argon gas with the pressure of about 3×10^{-2} Pa. The typical electron temperature was about 0.1 eV. The magnetic field inside the chamber was controlled by three pairs of Helmholtz coils.

The configuration of the equipments is schematically shown in Fig. 3. The impedance probe with a spherical sensor, whose radius was 3.5 cm, was used as a reference.

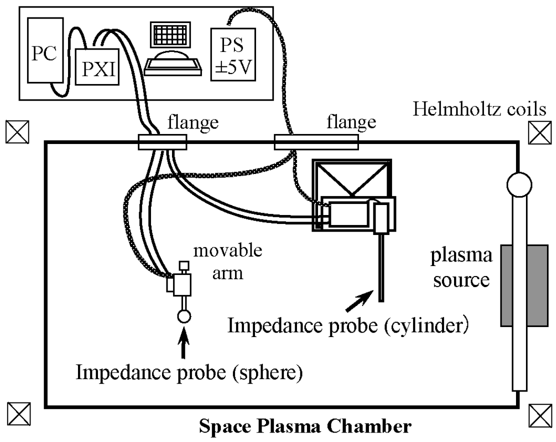

Fig.3 Configuration of the experiment. PS and PXI represent the ± 5V power supply and the integrated instrument (signal generator and digital oscilloscope), respectively.

3.2 Results

For the first experiment, magnetic field intensity was changed gradually within a range of 40,000-80,000 nT. The direction of the magnetic field was kept parallel to the cylindrical probe axis, which is confirmed to be the most favorable condition to observe the cyclotron harmonic resonances as described in the following paragraph. Figure 4 shows equivalent capacitance curves obtained by the cylindrical impedance probe. In these cases, the electron density was $3\text{-}4\times10^{5}$ cm^{-3} with the plasma frequency of about 5-6 MHz. The measured equivalent capacitance shows clear signature of the UHR and SHR in each panel. In addition to these major resonances which are predicted on the basis of the cold plasma theory, we can see an extra peak (indicated by white arrows) near the $2f_c$. This resonance frequency moved away from $2f_c$ with decreasing the magnetic field strength. The peak can be identified as the 2nd order of the series resonance whose frequency was modulated by the sheath capacitance. It is also found that the equivalent capacitance values at the 2nd cyclotron harmonic resonance frequency showed larger values than those of the SHR in Fig. 4 (a)-(c). Moreover, a local minimum of the equivalent capacitance (indicated by black arrows) other than the UHR can be found at slightly higher frequency than the cyclotron frequency. The dip was a parallel resonance in the thermal plasma, which was mentioned in Section 2.

In the second experiment, the angle between the axis of the probe sensor and the magnetic field line θ was controlled with maintaining the magnetic field intensity of 50,000 nT (i.e., f_c=1.4 MHz). Figure 5 represents results of the experiment. The cyclotron harmonic series resonances are indicated by white arrows. In the case the static magnetic field was parallel to the impedance probe (Fig. 5 (a)), we detected the 2nd, 3rd, and even 4th harmonic resonances. In contrast, the higher order of the resonances disappeared when the angle θ became close to a right angle. Increasing θ also made it difficult to identify the 2nd harmonic resonance.

We also performed an experiment with changing condition of the electron density, although the result is not explicitly shown in the paper. The experiment confirmed that the cyclotron harmonic resonances came to be clearer according to increase of the electron density. For example, the capacitance value at the 2nd order series resonance in Fig. 4 (b) shows much larger than the one in Fig. 5 (a) while the magnetic field intensity and the angle

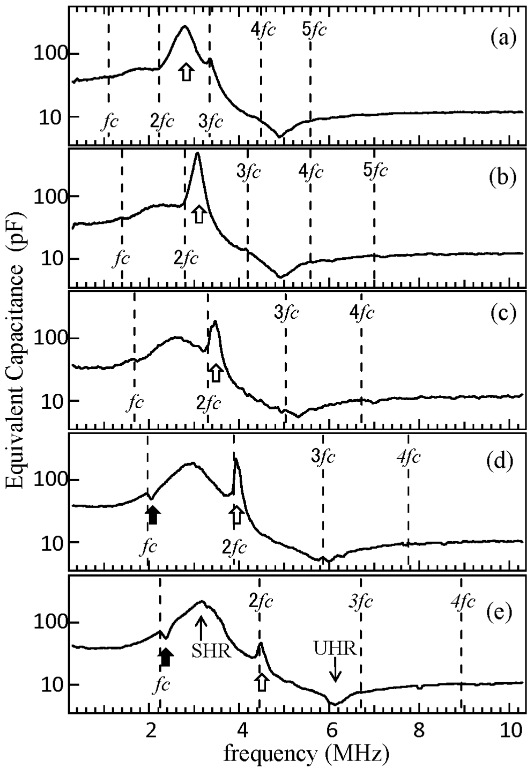

Fig.4 Variation of the probe equivalent capacitance depending on the magnetic field intensity. The cylinder probe was used. The magnetic field line was aligned along the probe axis. (a) f_c=1.12 MHz, (b) f_c=1.40 MHz, (c) f_c=1.68 MHz, (d) f_c=1.96 MHz, and (e) f_c=2.52 MHz, respectively.

θ are the same. The result denotes the same tendency of the resonances in a cold plasma, the SHR and UHR.

The cyclotron harmonic resonances were also found in experiments using the spherical impedance probe; however, the resonances were not clear comparing with the results of the cylinder probe experiments.

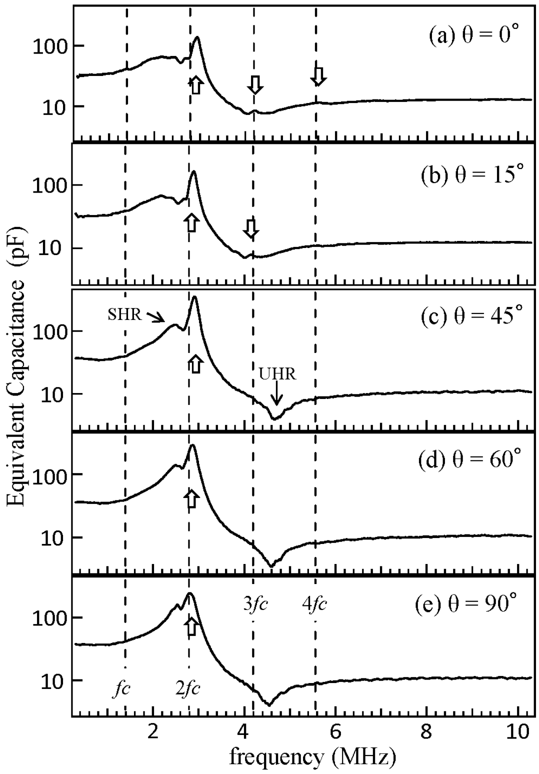

Fig.5 Variation of the probe equivalent capacitance depending on the angle between the cylindrical probe axis and the magnetic field. The electron cyclotron frequency was f_c=1.40 MHz. The plasma frequency was f_p=4.3-4.6 MHz.

4. Discussion and Conclusions

We investigated the kinetic effect of plasma on the impedance probe measurements, which was most likely attributed to the effect of the electrostatic cyclotron waves.

There are the series and parallel resonances related to harmonics of the electron cyclotron frequency, due to a character of the perpendicular permittivity in the thermal plasma. We also detected the resonances successfully by a laboratory experiment. It was confirmed that the cyclotron harmonic resonances appeared most clearly when the magnetic field was parallel with the cylindrical probe axis; and the cyclotron harmonic resonances were not clear in the case of the sphere probe measurement. It is essential for understanding these results to evaluate the antenna impedance including not only $\varepsilon_\perp$ but also the parallel permittivity $\varepsilon_\parallel$.

In a case where the cyclotron harmonic resonances are clear, the resonances will disturb the determination of the UHR frequency and derivation of the electron number density (see Fig. 1, 5). Therefore, the careful data calibration is needed.

The equivalent capacitance at the 2nd series resonance frequency sometimes showed unexpectedly large values (see Fig. 4 (a), (b)). In that case, the shift of the resonance frequency from $2f_c$ was also large. Mind that the resonance frequency is not f_Q, because the resonance frequency is lower than the UHR frequency. One possible interpretation will be that a plasma inhomogeneity at the sheath region surrounding the probe contributed to form such an anomalous peak by making the efficient energy absorption. The collisionless energy absorption in the cold inhomogeneous plasma was reported by previous works [23,24]; however, it is a difficult work to evaluate theoretically the impedance of antenna in the thermal plasma involving the ion sheath. The issue will be deferred to the future studies.

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