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COUPLING OF HELICON ANTENNAS TO PLASMA NEAR THE ELECTRON CYCLOTRON RESONANCE

Two inductive antennas, which are usually used for the excitation of a helicon discharge on the wave azimuthal modes $m = 1$ and $m = 0$, demonstrate unexpectedly different properties near the electron-cyclotron frequency ω_{ce}. Though the alternating inductive electric field $\widetilde{E}$ produced by the antenna $m = 1$ is mainly parallel to the external steady magnetic field B_0, nevertheless the absorption resonance at the frequency ω_{ce} accompanied by an increase in the plasma density, takes place. For the $m = 0$ antenna, where these fields are mutually transverse and where the cyclotron resonance seems certainly must be present, it is absent. But the electron-cyclotron resonance (ECR) appears again provided the B_0 field is turned up by the right angle around the same $m = 0$ antenna.

Keywords: helicon discharge, electron-cyclotron resonance, inductive antenna.

1. Introduction

Helicon discharges in a frequency range $\omega \ll \omega_{ce}$ are widely used for the dense ($\omega_{pe} > \omega$) plasma production. Near the cyclotron frequency ω_{ce}, the refractive index of helicon waves grows, and, in the electron-cyclotron resonance (ECR) region $\omega = \omega_{ce}$, these waves are being absorbed, transferring their energy to plasma electrons. This mechanism is used in ECR sources of multicharge ions, in which the electromagnetic energy is introduced from the side of a high magnetic field ($\omega_{ce} > \omega$) and then is carried by helicons to the absorption region $\omega = \omega_{ce}$. Here, the electron heating to a necessary high temperature takes place.

In the helicon sources of low-temperature plasma, this situation may arise, when one uses a nonuniform magnetic field in order to enhance the discharge efficiency. For this purpose, the magnetic field in the antenna region is reduced and can take the resonant value. This case was examined in work [1], where the efficiency of a helicon plasma source was compared in the presence or absence of the resonant field in the region of the inductive antenna. The authors had not revealed any difference between these two cases. A possible reason for such result, besides the obvious too high magnetic field gradient and, consequently, too narrow resonance zone, also may be an unsuitable antenna design. In that work, the antenna for the excitation of the first azimuthal mode $m = 1$ (m is the azimuthal number) of helicon waves was used. In the main discharge volume, it produces an inductive RF electric field $\widetilde{E}$ parallel to the external magnetic field B_0 ($\widetilde{E} \parallel B_0$), which does not satisfy the ECR conditions.

It seems possible that the azimuthally symmetric antenna of the $m = 0$ mode, which produces an electric field transverse to the magnetic one, $\widetilde{E}_\theta \perp B_0$, has essential advantages in the excitation of the cyclotron resonance. This induced us to compare properties of two inductive antennas assigned for the excitation of the azimuthal modes $m = 1$ and $m = 0$ of helicon waves, at magnetic fields close to the electron-cyclotron resonance. Since, in our experiments, the

RF generator frequency is fixed, the resonant properties of these antennas are measured vs the magnetic field strength.

2. Experimental Device

Schematically, the experimental setup is shown in Fig. 1. The cylindrical quartz discharge chamber of 14 cm in diameter and 23 cm long was situated in the longitudinal magnetic field B_0. One of two types of inductive antennas was placed on the chamber surface. The first was the so-called "frame antenna" 19 cm in length, which produced the RF magnetic field $\widetilde{B} \perp B_0$ transverse to the axis and generated the azimuthal mode $m = 1$ of helicon waves (Fig. 1, a).

Another was the two-turn antenna, whose RF magnetic field was parallel to the axis $\widetilde{B} \parallel B_0$. It excited the azimuthally symmetric mode $m = 0$ (Fig. 1, *b*). On the left, the chamber was closed with a metal flange; on the right, it was attached to the vacuum system.

An external magnetic field B_0 parallel to the chamber axis was produced by two annular coils with internal diameters of 23 cm and 11 cm in length, which were placed around the chamber at a distance 8 cm each from other (Fig. 1, *a*, *b*). The magnetic field was calibrated according to the coil current with the use of a Hall magnetometer; Earth's magnetic field was not taken into account.

Through a conventional capacitive matching circuit, the antennas were connected to the RF generator with a frequency of 13.56 MHz and up to 1 kW in power. The chamber was filled with argon gas at a pressure from 0.12 to 0.4 Pa. Without magnetic field B_0 in the presence of the RF antenna current, an inductive discharge was initiated in the chamber. The light from the discharge was accepted by a photoreceiver, which was collimated to the middle part of the chamber between the coils and then was registered with a two-coordinate recorder as a function of the current in the coils (i.e. of the magnetic field B_0). Using an 8-mm interferometer, it is established that the discharge light intensity is approximately proportional to the plasma density.

3. Experimental Results

1) The frame antenna of the $m = 0$ mode in a longitudinal magnetic field (Fig. 1, *a*) produces the high frequency magnetic field transverse to the axis, $\widetilde{B} \parallel B_0$. The induced electric field $\widetilde{E}$ is directed mainly along the linear antenna conductors, in parallel to the external magnetic field, and does not affect the cyclotron motion of electrons. Only near the ends of antenna, the induced electric field becomes perpendicular to the magnetic field and can cause the cyclotron heating of electrons [2,3]. Nevertheless, the frame antenna demonstrates an abrupt rise of the density (plasma luminosity) at the resonant magnetic field $\omega_{ce}/\omega = 1$, as is shown on the right in Fig. 1, *a*. For a frequency of 13.56 MHz, the resonant field is only $B_{\text{res}} = 4.85 \times 10^{-4}$ T, but it essentially influences the discharge parameters. At the resonance, the RF antenna current decreases by 2–2.5 times comparing with its initial (at $B_0 = 0$) value. The especially narrow resonance is observed at low pressures. In Fig. 1, *a*, the lower curve was obtained at an argon pressure of 0.12 Pa, the upper one corresponds to a pressure of 0.2 Pa at the RF power $W = 100$ W. The increase of the pressure and the RF power makes the resonance less distinct. At a further increase of the magnetic field, the plasma density grows again, and the discharge acquires the helicon nature.

2) The azimuthally symmetric antenna of the $m = 0$ mode in a longitudinal magnetic field $B_0 \parallel Z$ is shown in Fig. 1, *b*.

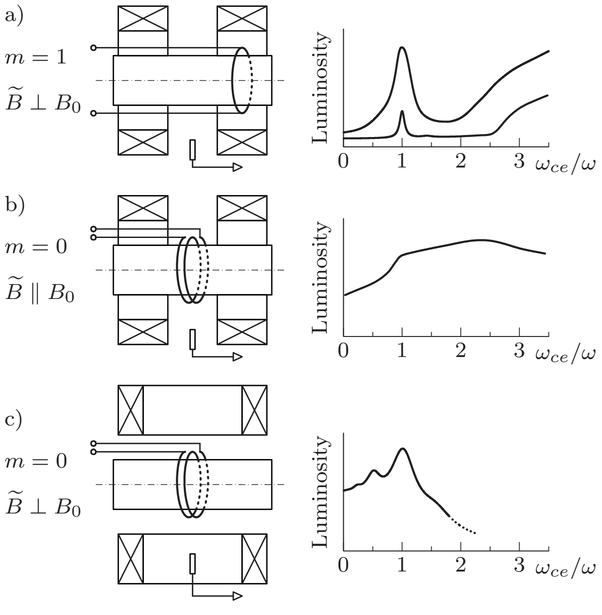

Fig. 1. Schematic diagram of experimental devices and experimental results

Its RF magnetic field is parallel to the external field, $\widetilde{B} \parallel B_0$, and the induced electric field $\widetilde{E}_\theta$ is directed along the azimuth perpendicularly to the magnetic field $\widetilde{E}_\theta \perp B_0$. This configuration seems to be the most favorable for the manifestation of the ECR resonance. However, in our experiment under the same conditions as in the previous case (pressure $p_{\mathrm{Ar}} = 0.2$ Pa, RF power $W = 100$ W), no sign of the resonance at $\omega_{ce}/\omega = 1$ was observed (right in Fig. 1, *b*).

3) The same azimuthally symmetric antenna of the $m = 0$ mode, but in a *transversal* magnetic field $B_0 \perp Z$ (Fig. 1, *c*). In order to find out a reason for the last result, the magnetic coils were taken off and placed on both sides of the discharge chamber. So, they produced the magnetic field B_0 transverse to the chamber axis (Fig. 1, *c*). The distance between the coils had to be enlarged up to 18 cm, and, as a result, the maximal field strength decreased, and the field uniformity got worse. Now again, the RF magnetic field of the antenna $\widetilde{B}$ becomes perpendicular to the external field $\widetilde{B} \perp B_0$. As is seen from Fig. 1, *c*, the resonance at $\omega_{ce}/\omega = 1$ is certainly observed again under the same conditions ($p_{\mathrm{Ar}} = 0.2$ Pa, $W = 100$ W), provided the cyclotron frequency is calculated by the value of magnetic field in the middle plane between the coils. Simultaneously, some vague resonances are observed on harmonics of the cyclotron frequency at $\omega_{ce}/\omega = 1/2$ and $\omega_{ce}/\omega \approx 1/4$.

4. Discussion

1) The resonance at $\omega_{ce}/\omega = 1$ in the $m = 1$ antenna may be caused by RF electric fields near the antenna ends. In the main part of the volume, the induced electric field $\widetilde{E}_Z$ is directed along the linear conductors in parallel to the magnetic field. But because of their inductive nature, the electric field lines must be circularly closed and have to pass across the magnetic field B_0 at the antenna ends. The same transversal direction is revealed by the electric field of a plasma polarization [3]. However, these reasons for the resonance origin seem to be rather indirect, and its distinct manifestation at the main frequency ω_{ce} with the $m = 1$ antenna is unexpected. With increase of the pressure up to 0.4 Pa, the electron-neutral collision frequency amounts to the cyclotron frequency, and the resonance becomes less clear. At an increase of the RF power up to W $\approx$ 1 kW, the amplitude of the RF magnetic field produced by the antenna attains $\widetilde{B} = (2.5 - 3) \times 10^{-4}$ T and becomes comparable to the resonant field strength B_{res}. This disturbs the electron rotation synchronism and decreases the quality of the resonance. The increase of the magnetic field far above B_{res} leads to a growth of the plasma density, and the discharge proceeds to the helicon regime. In this state in contrast to the ECR absorption resonance, the "geometrical" resonances due to the formation of standing helicon waves are possible. Resonances of this type were investigated also in [4]. In the present work, this region of magnetic fields is not considered.

The resonant influence of a transversal magnetic field on the inductive discharges was revealed long ago, at working out the RF ion sources for accelerators of nuclear particles [5]. These resonances were observed at magnetic fields exceeding the cyclotron value, at $\omega_{ce}/\omega \approx 2.5$–3.

The subsequent investigations showed that these resonances were a result of the formation of standing helicon (electron-cyclotron) waves [6]. Really, from the dispersion relation

$$\frac{k^2c^2}{\omega^2} = \frac{\omega_{pe}^2}{\omega(\omega_{ce} - \omega)},$$

where c is the speed of light, k – wave number, ω_{pe} – plasma frequency, it is seen that, at $\omega = \omega_{ce}/2$, the wavelength of the electron-cyclotron wave is $\lambda \sim\sim 2\pi c/\omega_{pe}$.

For a typical density of 1.5×10^{11} cm^{-3}, this gives $\lambda/2 \sim 4$ cm that is close to the discharge chamber size of RF ion sources of this type. The resonance at the main frequency ω_{ce} in those works might be missed due to a higher pressure, a higher RF power, or the insufficient magnetic field uniformity, to which the geometrical resonances are not too sensitive.

2) The absence of the cyclotron resonance in the azimuthally symmetric antenna $m = 0$ seems to be unexpected, and we have no simple explanation to it. A possible reason may be the narrow space, where the azimuthal inductive field E_θ exists. Assuming this width to be about the antenna radius $\sim$7 cm, we obtain that, at the typical (of the helicon discharges) electron temperature $T_e = 4$ eV, the electron passes through this region for a time of $\sim 4 \times 10^{-8}$ s, which is about a half of the cyclotron (generator) period 7.35×10^{-8} s.

But the similar arguments are applicable to the $m = 1$ antenna, at which the resonance $\omega_{ce}/\omega = 1$ is clearly expressed. It have been experimentally shown also that the distributed capacitive electric field between the linear conductors of the $m = 1$ antenna could not produce any resonance effect.

3) Appearance of the resonance at the $m = 0$ antenna after changing the B_0 field direction seems to be reasonable, because this arrangement partly reproduces the previous configuration with the frame $m = 1$ antenna. Now, the magnetic fields again are mutually transverse, but with a less length of the plasma column along B_0. For a greater distance between the coils (18 cm) the B_0 field uniformity became worse. This causes a broadening of the resonance, because the resonant conditions are satisfied now at various coil currents in different parts of the chamber.

At $\omega_{ce}/\omega < 1$, there are no plasma waves propagating along the magnetic field, and the weak resonances in Fig. 1, *c* in this region are probably connected with the Bernstain modes on higher harmonics of the electron-cyclotron frequency.

5. Conclusions

Near the electron-cyclotron frequency ω_{ce}, the particular resonant properties of two different inductive antennas usually used for the helicon discharge excitation have been demonstrated. It is shown that this difference results only from the mutual orientation of the RF magnetic field $\widetilde{B}$ produced by the antenna and the external direct magnetic field B_0. The resonance on the cyclotron frequency ω_{ce} takes place, when these fields are mutually transverse, and it is absent, when they are parallel. Since the cyclotron mechanism demands the existence of an RF electric field component perpendicular to the magnetic field, $\widetilde{E}_\theta \perp B_0$, the observed difference may clarify the field structure excited by different inductive antennas in plasma.

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ЗВ'ЯЗОК ГЕЛІКОННИХ АНТЕН З ПЛАЗМОЮ БІЛЯ ЕЛЕКТРОННО-ЦИКЛОТРОННОГО РЕЗОНАНСУ

Резюме

Дві індукційні антени, які зазвичай використовуються для збудження геліконних розрядів на хвилях азимутальних мод $m = 1$ та $m = 0$, демонструють неочікувано відмінні властивості поблизу електронно-циклотронної частоти ω_{ce}. Хоча індукційне змінне електричне поле $\widetilde{E}$, утворюване антеною $m = 1$, є переважно паралельним до зовнішнього магнітного поля B_0, тим не менше на частоті ω_{ce} спостерігається резонанс поглинання, що супроводжується зростанням концентрації плазми. Для антени $m = 0$, у якої ці поля перпендикулярні і де такий резонанс, здавалося б, неодмінно повинен бути, він відсутній. Проте ЕЦР резонанс виникає знову, якщо поле B_0 розвернути під прямим кутом навколо тієї самої $m = 0$ антени.