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V.F. VIRKO, YU.V. VIRKO

Institute for Nuclear Research, Nat. Acad. of Sci. of Ukraine
(47, Nauky Ave., Kyiv 03028, Ukraine; e-mail: y.v.virko@gmail.com)

INFLUENCE OF NONUNIFORM MAGNETIC FIELD ON THE HELICON DISCHARGE EXCITED BY VARIOUS ANTENNAS

The influence of a nonuniform magnetic field, which increases with the distance from an inductive antenna, on a helicon discharge has been studied. The discharge was excited in the azimuthally symmetric mode of helicon waves, $m = 0$, making use of antennas of two different types. It is shown that if the discharge is produced by a loop antenna, which supplies the RF energy through the side boundary of plasma and perpendicularly to the external magnetic field, then the ionization is concentrated at the discharge periphery. Under those conditions, the imposing of a nonuniform magnetic field reduces the loss of ionizing electrons at the wall and enhances the plasma generation. If the discharge is excited with a planar antenna along the magnetic field, then the main ionization occurs in the inner plasma region around the axis. In this case, an increase in the plasma density, if any, may be a result of the plasma contraction in the magnetic field with force lines convergent to the axis.

Keywords: helicon discharge, nonuniform magnetic field, induction antennas.

1. Introduction

A helicon discharge in the azimuthally symmetric helicon wave mode can be formed with the help of induction antennas of two different types. One of them is a one- or two-turn loop antenna encircling a cylindrical quartz discharge chamber. The other so-called "planar" antenna is a flat spiral composed of a few turns mounted at a flat dielectric (quartz) window at the chamber end. The both antennas create a high-frequency magnetic field that is parallel to the external magnetic field. In such a way, they excite an azimuthally symmetric helicon wave with the azimuthal number $m = 0$ [1, 2]. The difference between those two antenna types consist in that the loop antenna introduces the electromagnetic energy into the discharge from the plasma periphery perpendicularly to the external magnetic field lines. At the same time, the RF energy flux from the planar antenna is directed along the field, i.e., in parallel to the chamber axis.

Earlier, it was found that if the stationary magnetic field in the region, where the induction antenna is located, is lower, so that the field increases with the distance from the antenna, then, provided the same supplied RF power, the plasma concentration in the helicon discharge can be made several times higher in comparison with the case of uniform field. This phenomenon was observed for the first time by F. Chen *et al.* [3] in a discharge generated in the first azimuthal mode, $m = 1$, of helicon waves. Later, it was confirmed for a discharge with $m = 0$ excited with a loop antenna [4–6]. Although the mechanism of growth of the plasma concentration has not been elucidated in detail, we supposed in work [5] that one of the causes could be a detachment of the plasma generation region from the chamber wall. In this case, the losses of hot electrons that are formed in a thin external plasma layer owing to the peripheral absorption of he-

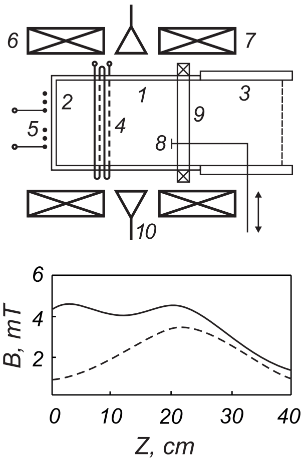

Fig. 1. (Upper panel) Schematic diagram of the experimental device: discharge chamber (*1*), quartz window (*2*), metal section (*3*), loop antenna (*4*), planar antenna (*5*), magnetic field coils (*6, 7*), planar Langmuir probe (*8*), diamagnetic loop (*9*), 8-mm interferometer (*10*). (Bottom panel) Axial distributions of uniform (solid curve) and nonuniform (dashed curve) magnetic fields at a current of 7.5 A through the coils

licon and Trivelpiece–Gould waves [7] diminish. However, in some other experiments [8, 9], neither a significant enhancement of plasma generation in a nonuniform magnetic field was observed, nor the existence of a layer of high-energy electrons at the plasma boundary was detected. The authors of work [8] explained a certain increase of the plasma density by a simple plasma contraction along the magnetic force lines that converged to the discharge axis.

The helicon discharge with a planar antenna has substantial advantages, when practically implementing a plasma source for technological applications. First, a separate discharge chamber is not required [1], and the processed surface can be arranged oppositely to the quartz window with the antenna, which strongly simplifies the equipment arrangement. Second, such an antenna has no length along the magnetic field, so that it is a localized source and excites waves with a continuous spectrum of wave numbers in the direction of wave propagation. Therefore, the planar antenna does not create additional "antenna" resonances, which can also induce concentration jumps and complicate the maintenance of a stable discharge mode. Owing to those advantages, the discharge with a planar antenna is more and more implemented in the plasma-technological processes. A possibility to improve this discharge by applying a nonuniform magnetic field would have an important value.

The results of previous studies carried out under different experimental conditions are insufficient. Some of them point to a positive effect of the nonuniform field on the discharge with a planar antenna. In particular, the range of magnetic fields, in which a stable discharge can be maintained, becomes wider, the discharge ignition becomes easier, and the plasma concentration increases [10]. At the same time, in some other experiments, the plasma concentration in a nonuniform field remained almost unchanged [11]. Therefore, the aim of this work was to compare the influence of a nonuniform magnetic field on the helicon discharge, when the latter is excited making use of either a loop or planar antenna under the same experimental conditions in the interval of weak magnetic fields ($B_0 < 10$ mT).

2. Experimental Device

The schematic diagram of the experimental setup is depicted in the upper panel of Fig. 1. The installation included cylindrical quartz discharge chamber (*1*) 14 cm in diameter and 23 cm in length. One of its ends was flat quartz window (*2*) 12 mm in thickness. At the other end, the chamber was connected to metal section *3* with the same diameter and 14 cm in length, which ended with a grid made from a perforated copper sheet, through which the gas was pumped out. Two-turn loop antenna (*4*) 15 cm in diameter was mounted at a distance of 6 cm from the quartz window. Four-turn planar antenna (*5*) with an external diameter of 9.5 cm and an internal diameter of 5.5 cm was mounted closely to the window. The both antennas were made of a copper tube 4 mm in diameter and were cooled with water.

The discharge chamber was placed into a longitudinal magnetic field formed by a system of two coils (*6, 7*), each with an internal diameter of 23 cm and a length of 12 cm, which were arranged at a distance of 8 cm from each other. Provided the same current of 7.5 A through the both coils, an approximately uniform magnetic field with an induction of 4.5 mT was formed within the discharge chamber volume. If the left coil (*6*) was switched-off, there arose an nonuniform field that grew with the distance from the antenna, as is shown by the dashed line in the bottom panel of Fig. 1. The coils were supplied with a current from a stabilized LIPS-35 source. With the help of a standard capacitive matching device, the antennas were connected to an RF generator with a frequency of 13.56 MHz and a power of up to 1 kW. The magnitudes of the incident and reflected powers (the matching degree) were measured by means of a directional coupler that the generator was equipped with. The experiments were carried out at an argon pressure of 0.65 Pa.

For plasma parameter measurements, planar Langmuir probe (*8*) 3.5 mm in diameter and with a protective ring with an external diameter of 6 mm and an internal diameter of 4 mm was used. The probe was oriented perpendicularly to the magnetic field lines and could move along the chamber diameter at a distance of 18 cm from the quartz window. An advantage of such a probe is the potential independence of the ion collection area and, as a result, the well-pronounced saturation of an ion current. No RF compensation methods were used to prevent the influence of plasma potential oscillations on the probe parameters [11].

The longitudinal electron temperature T_e was determined from the initial section of the electron branch in the probe characteristic. The plasma concentration was calculated from the ion saturation current density j_i, by using the Bohm formula $n_e = j_i(0.5eC_s)^{-1}$, where $C_s = (T_e/M_i)^{1/2}$ is the ion sound velocity. The probe characteristic was also used to determine the floating probe potential $\varphi_{\rm fl}$. The radial distribution of the floating potential $\varphi_{\rm fl}$ was registered by connecting the probe to a high-impedance (10 MΩ) recorder input.

At the same time, a planar probe was used to qualitatively research the amplitude distribution of high-frequency plasma-potential oscillations. For this purpose, a alternating component $i_{\rm RF}$ with a frequency of 13.56 MHz was extracted from the electron probe current with the help of a resonant circuit. After the detection, the component was recorded on a two-coordinate recorder at various radial probe positions. The amplitude of this signal at a fixed voltage across the probe qualitatively reflects the amplitude of plasma potential oscillations at a given radius.

To measure the plasma magnetization a diamagnetic loop (*9*), consisting of 100 wire turns and electrostatically shielded from the plasma, was placed at the chamber surface at a distance of 18 cm from the quartz window. An emf pulse induced owing to the magnetic field change, when the discharge was switched-off, was integrated by an active integrator and recorded by a storage oscilloscope S8-17. The discharge was switched-off by applying a negative locking voltage to the grid of an output tetrode in the RF generator.

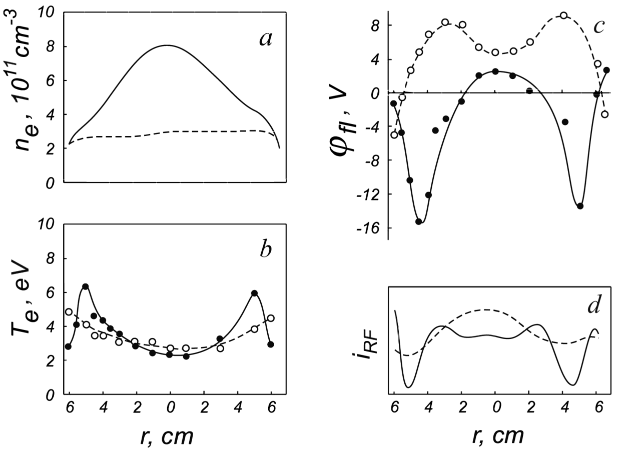

Fig. 2. Discharge excitation with a loop antenna. Radial distributions of concentration n_e (*a*), temperature T_e (*b*), floating potential $\varphi_{\rm fl}$ (*c*), and amplitude of RF oscillations of electron current through the probe $i_{\rm RF}$ (*d*) (qualitatively, it reflects the distribution of plasma potential oscillations) in a uniform (dashed curves) and a nonuniform (solid curves) magnetic field

The plasma density averaged over the diameter could be measured with the use of an 8-mm interferometer (*10*) mounted in the middle plane of a discharge chamber, in the gap between the magnetic coils.

3. Results of Measurements

The radial distributions of plasma parameters in the case of discharge excitation with a loop antenna are shown in Fig. 2. The dashed curves and hollow circles correspond to the results obtained at a discharge in a uniform magnetic field with an induction of 4.5 mT (at a current of 7.5 A through the coils). The solid curves and solid circles correspond to the case of nonuniform field, when the left coil (*6*, see Fig. 1) was switched-off. The measurements were carried out at an absorbed RF power of about 1 kW.

Figure 2, *a* demonstrates the distribution of the saturation ion current recalculated into the plasma concentration n_e (the electron temperature T_e was taken to be approximately equal to 4 eV) at the probe potential $U_{\rm p} = -30$ V. As one can see, the plasma density in a nonuniform field increases over

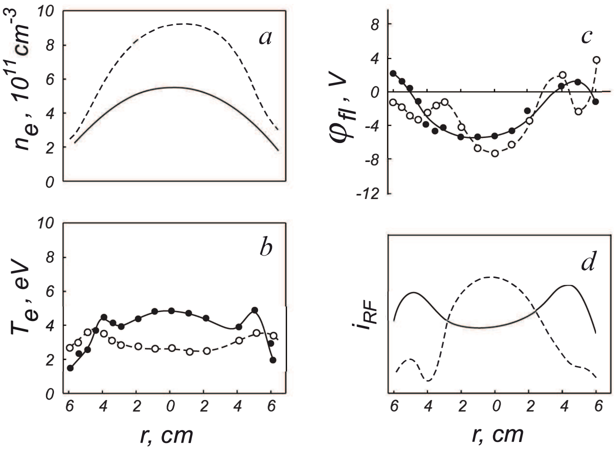

Fig. 3. Discharge excitation with a planar antenna. Radial distributions of concentration n_e (*a*), temperature T_e (*b*), floating potential $\varphi_{\rm fl}$ (*c*), and amplitude of RF oscillations of electron current through the probe $i_{\rm RF}$ in a uniform (dashed curves) and a nonuniform (solid curves) magnetic field (*d*)

the whole discharge cross-section. In both cases (uniform and nonuniform magnetic fields), the electron temperature T_e (Fig. 2, *b*) reaches maximum values at the plasma periphery. In the nonuniform field (solid curve), the temperature grows by a factor of two and reaches a value of 6.5 eV at a distance of 1.5–2 cm from the wall. At the same time, it equals only 2.3 eV at the plasma axis. The floating potential $\varphi_{\rm fl}$ (Fig. 2, *c*) is negative at the plasma periphery. In the nonuniform field, it reaches values from -13 to -15 V, which also indicates the presence of high-energy electrons in this region. At the discharge axis, the floating potential is positive and varies from $+3$ to $+5$ V in a qualitative correspondence with the electron temperature distribution. The amplitude distributions for the high-frequency component of the electron current, $i_{\rm RF}$, are illustrated in Fig. 2, *d* in arbitrary units. The curves demonstrate that the amplitude of plasma potential oscillations at the plasma periphery is smaller than near the plasma axis, especially in the case of nonuniform field.

The results of analogous measurements, but in the discharge excited with a planar antenna, are shown in Fig. 3. The notations are the same as in Fig. 2: the dashed curves and hollow circles correspond to a discharge in a uniform field, whereas the solid curves and solid circles to a discharge in a nonuniform field. The attention is drawn by a high efficiency of the planar antenna. If the supplied RF power is high enough, the planar antenna provides a higher plasma concentration even in a uniform magnetic field than the loop antenna does in a nonuniform one. However, the generation of such a discharge, when using a planar antenna in a homogeneous field of 4.5 mT and at a power absorption of about 1 kW, is a significantly more difficult task. For the ignition of this discharge, the magnetic field has to be considerably reduced, and the required parameter values have to be reached gradually, by simultaneously increasing both the field and the RF power, and monitoring their agreement. Indeed, if a certain critical magnitude of the uniform magnetic field is exceeded, the discharge breaks down, and the reflected power increases in excess.

From Fig. 3, *a*, it is evident that the application of a nonuniform field under our experimental conditions does not increase the plasma concentration in the case of discharge with a planar antenna. On the contrary, the plasma density considerably diminishes in a nonuniform field. But, unlike the uniform field case, the discharge in nonuniform fields (the solid curves) can be easily matched in a wide interval of magnetic fields.

The radial distributions of the electron temperature are depicted in Fig. 3, *b*. They do not reveal a substantial elevation of T_e at the plasma periphery in comparison with the inner plasma region. Accordingly, the floating potential acquires the largest negative values near the discharge axis (Fig. 3, *c*). The amplitude of the high-frequency component of the electron current, which qualitatively reflects the distribution of plasma potential oscillations (Fig. 3, *d*), has a maximum at the axis in the case of uniform field. However, this amplitude is approximately identical over the discharge cross-section in the case of nonuniform field.

Figure 4 exhibits the results of the study dealing with the magnetic properties of plasma in the discharge excited with a loop (Fig. 4, *a*) or planar (Fig. 4, *b*) antenna. The signal of a diamagnetic loop was calibrated in the plasma absence with the help of a uniform magnetic field created by the coils with a known current. If a rapid switch-off of the discharge gives rise to a certain growth of the external magnetic field, this fact indicates that the induction is reduced by $-\Delta B < 0$ in the presence of plasma (diamagnetism). In the opposite case, the presence of plasma increases the external field by $+\Delta B > 0$ (paramagnetism). The plots in Fig. 4 illustrate the dependence of the ΔB-value on the current I_B through the magnetic coils in the cases of uniform (dashed lines) and nonuniform (solid lines) fields. By changing the RF power, the plasma concentration – i.e. its value averaged over the plasma cross-section and measured with a microwave interferometer – was maintained at an approximately constant level of 4.5×10^{11} cm^{-3}. As one can see from Fig. 4, *a*, the discharge with a loop antenna manifests paramagnetic properties in a uniform field, which transform into diamagnetic ones in a nonuniform field. On the contrary, the plasma discharge with a planar antenna (Fig. 4, *b*) is diamagnetic in the both cases.

4. Discussion of the Results

As one can see from Fig. 2, *a*, if the discharge is excited with the help of a loop antenna in a nonuniform field, the concentration increases over the whole plasma cross-section, i.e., the number of charged particles per unit length of a plasma column,

$$N = 2\pi \int_{0}^{R} n_e(r) r dr,$$

increases. This result confirms that, under our experimental conditions, the plasma density increases due to the ionization growth, rather than as a result of the simple plasma contraction along the magnetic field lines, as perhaps was observed in work [8]. In the latter case, together with the concentration growth at the axis, a reduction of the concentration at the discharge periphery should have taken place. The origin of the ionization rate growth can be seen from the radial temperature profile depicted in Fig. 2, *b*. In the uniform field, the temperature maximum $T_e = 5$ eV is observed immediately near the discharge chamber wall. At the same time, in the nonuniform field, the temperature T_e grows near the wall and reaches a value of 6.5 eV at a distance of 1.5–2 cm from it.

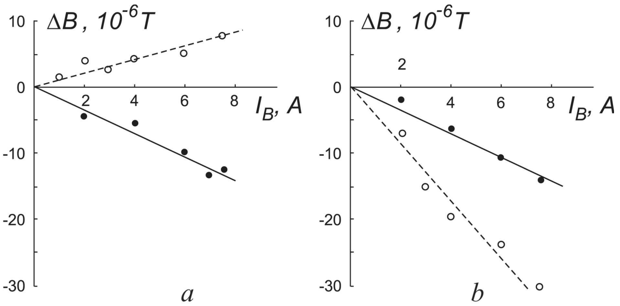

Fig. 4. Diamagnetic signal of a discharge with a loop (*a*) or a planar (*b*) antenna. The plots illustrate the dependences of the change ΔB of the external magnetic field induction in plasma at the discharge in uniform (dashed lines) and nonuniform solid lines) fields on the current I_B through the magnetic coils

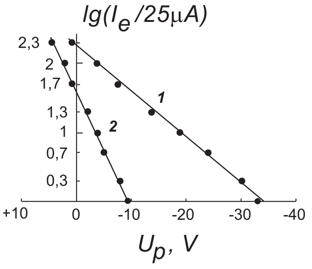

Fig. 5. Probe characteristics in a discharge plasma with a loop antenna in a nonuniform magnetic field. Points *1* ($r = 5$ cm, $T_e = 6.5$ eV) and *2* ($r = 0$, $T_e = 2.3$ eV) correspond to characteristics in Fig. 2, *b*

Note that, although the plasma concentration at the periphery is lower than that at the axis, the number of electrons with energies exceeding the argon ionization potential is tens times as large here owing to the temperature difference. Therefore, the ionization mainly occurs at the plasma periphery. This region is separated from the chamber wall by the layer of a colder plasma with a temperature of 3–4 eV. Such isolation is also a result of the plasma compression by the magnetic field. But its main effect, in our opinion, consists in a reduction of hot electron losses at the chamber wall, which stimulates the additional heating and additional plasma generation. The authors of work [8] did not observe a substantial temperature growth at the discharge boundary. Since the probe used by us did not possess a proper RF compensation [12], the doubts concerning the presence of a peripheral layer with an elevated temperature (6.5 eV) may be associated with a probable distortion of the probe characteristic by potential fluctuations, which results in the temperature overestimation [12].

Nevertheless, such distortion usually gives rise to a deviation of the electron branch in the characteristic from the exponential growth. As a result, the characteristic is no more a straight line on the semilogarithmic scale. Figure 5 exhibits the logarithm of the electron current in the initial section (from 25 μA to 5 mA) for two characteristics that correspond to the points of the solid curve in Fig. 2, *b* with the radial coordinates $r = 5$ cm (straight line *1*, $T_e = 6.5$ eV) and $r = 0$ (straight line 2, $T_e = 2.3$ eV). As one can see, both characteristics are linear within the interval of the electron current changing by two orders of magnitude. In addition, as is shown by the solid curve in Fig. 2, *d*, the amplitude of RF potential oscillations at the discharge axis substantially exceeds the same amplitude at the radius $r = 5$ cm. But a temperature of 2.3 eV at the axis can hardly be overestimated, i.e., the available potential oscillations did not affect the result of its measurement. An even weaker influence should be expected near the wall at $r = 5$ cm, where the oscillation amplitude is much smaller, probably due to the wave absorption in this region.

An additional confirmation of the presence of a peripheral layer with hot electrons in a nonuniform field is the high negative potential of a floating probe in this zone, as is illustrated in Fig. 2 by a solid curve. These data completely support our previous results obtained in work [5]. A probable origin of their discrepancy with the results obtained in work [8], besides the difference between the discharge parameters and between the antenna types (in work [8], a "twisted" antenna in the mode $m = +1$ was used), may be the fact that, in the mentioned experiments, plasma flows from the source into the drift chamber with a considerably larger diameter and, as a result, does not contact with the wall even in a uniform field. Therefore, the plasma contraction in a nonuniform field does not affect the balance of high-energy electrons and does not create additional ionization.

The influence of a nonuniform magnetic field on the discharge excited with a planar antenna has substantial differences. First, the field nonuniformity does not result in the plasma concentration growth, as was in the previous case. On the contrary, as is shown in Fig. 3, *a* (solid curve), the plasma density decreases in a nonuniform field under our experimental conditions. A possible cause consists in that the planar antenna was arranged farther at the end of the magnetic system. So, when left coil (*6*) was switched-off, the planar antenna turned out located in a too weak magnetic field (see Fig. 1). Because of the larger ratio between the magnetic fields at the places of concentration measurement ($z = 18$ cm) and planar antenna location ($z = 0$) (the cork ratio), the plasma reflection phenomenon may be more important as compared with the case of loop antenna.

At the same time, as was already noted, the ignition and maintenance conditions for the discharge with a planar antenna become strongly improved in a nonuniform field. This conclusion is in accordance with the results of other works [3,5]. The radial distributions of the temperature (Fig. 3, *b*) and the floating potential (Fig. 3, *c*) testify that if a discharge is excited with a planar antenna, whose diameter is smaller than the diameter of a discharge chamber, plasma is mainly generated in the inner discharge region, which does not have significant losses of ionizing electrons at the wall even in a uniform magnetic field. That is why the additional plasma compression in a nonuniform field stimulates no additional plasma generation.

Those assumptions are confirmed by plasma diamagnetism measurements. As is shown in Fig. 4, *a*, the discharge plasma excited with a loop antenna increases the external magnetic field, $\Delta B > 0$, in a uniform field (dashed straight line). This scenario can be realized in the case where the plasma diamagnetism is completely compensated by the boundary paramagnetic current, which arises owing to the plasma contact with the wall. At the same time, since the pressure gradient in plasma is directed outward, the drift current also has the paramagnetic direction. In a nonuniform field, the plasma boundary becomes free, and the boundary diamagnetic current exceeds the drift current in the inner plasma region (the solid line in Fig. 4, *a*).

In the case of planar antenna (Fig. 4, *b*), plasma exhibits diamagnetic properties, $\Delta B < 0$, in both uniform and nonuniform fields. If the RF power is introduced along the magnetic field, the electron heating and the plasma generation take place mainly in the internal discharge region. As a result, the electron concentration and temperature at the periphery turn out insufficient to create a drift current that would be capable of compensating the plasma diamagnetism.

5. Conclusions

To summarize, we have confirmed that, when exciting a helicon discharge with the use of a loop antenna in the mode $m = 0$, which introduces the RF energy in the direction from the plasma periphery across the magnetic field, there arises a layer of hot electrons at the plasma boundary. In a uniform magnetic field, this layer is in contact with the chamber wall, and the plasma demonstrates paramagnetic properties. In a nonuniform magnetic field with the force lines converging to the axis, this region becomes isolated from the wall, which results in the temperature elevation and the plasma concentration growth owing to a higher ionization. Plasma becomes diamagnetic at that.

When the discharge is excited along the magnetic field by means of a planar antenna, plasma is mainly generated in the internal discharge region irrespective of whether the field is uniform or not. In the both cases, the plasma exhibits diamagnetic properties, which testifies to the absence of a direct contact between the plasma generation region and the wall. Under those specific conditions, the application of a nonuniform field does not result in the concentration growth.

The results obtained confirm that an increase of the plasma concentration in a helicon discharge with a nonuniform magnetic field stems from a reduction of ionizing electron losses at the discharge chamber walls. If a planar antenna with the diameter smaller than the chamber diameter is used or if plasma flows into a drift volume with considerably larger dimensions, the plasma density growth may originate from the plasma contraction in a nonuniform magnetic field.

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В.Ф. Вірко, Ю.В. Вірко

ВПЛИВ НЕОДНОРІДНОГО МАГНІТНОГО ПОЛЯ НА ГЕЛІКОННИЙ РОЗРЯД, ЗБУДЖУВАНИЙ РІЗНИМИ АНТЕНАМИ

Резюме

Досліджено вплив неоднорідного магнітного поля, яке зростає з віддаленням від індукційної антени, на геліконний розряд, збуджуваний на азимутально симетричній моді геліконних хвиль $m = 0$ антенами двох типів. Показано, що коли розряд утворюється петльовою антеною, яка вводить ВЧ енергію через бокову границю плазми, перпендикулярно до зовнішнього магнітного поля, іонізація зосереджена на периферії розряду. В цих умовах, накладання неоднорідного поля зменшує втрати іонізуючих електронів на стінку і призводить до збільшення генерації плазми. При збудженні розряду планарною антеною вздовж магнітного поля, основна іонізація відбувається у внутрішній, приосьовій області плазми. В цьому випадку зростання густини плазми в неоднорідному полі, якщо воно має місце, може бути наслідком контракції плазми у магнітному полі, силові лінії якого сходяться до осі.