MODIFIED HELICON DISCHARGE EXCITED BY A LINEAR INDUCTIVE ANTENNA

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A new modification of the helicon discharge capable of producing linearly uniform plasma is investigated. The discharge is excited in magnetic field by an inductive antenna consisting of two parallel linear conductors with antiphase RF currents, similar to a two-wire transmission line. The wave nature of the discharge is demonstrated. It is shown that there exist some discharge conditions in which plasma density is homogenous along a significant part of the antenna length. A convenient for realization discharge system with the linear antenna immersed into plasma is proposed. Provided further improvement this discharge may be used for uniform plasma processing of large surfaces.

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INTRODUCTION

Further development of plasma technologies demands uniform processing of still larger area surfaces (as displays, solar batteries, light panels and so on). The use for these purposes of well known transformer coupled plasmas (TCP – discharges) [1] is limited for unacceptable increase thickness of the quartz window, capable to stand against the atmospheric pressure. A possible solution is to create plasma which is uniform along a single coordinate. Then, moving the surface in the transversal direction one can uniformly treat a sufficiently large area.

To produce linearly homogeneous plasma the application of distributed sources was proposed. Since the helicon discharge is one of the most efficient technological plasma sources, F.Chen *et al* [2] in USA developed a linear array of multiple small helicon discharges. The discharges were situated in such a way, that their density profiles, overlapping, gave approximately uniform plasma along this line. But the full solution of the problem was not yet achieved.

Another approach consists in such modification of the discharge that it itself can produce the linearly uniform plasma. For this aim the two-turn flat circular antenna (so called “planar” antenna), which in the magnetic field is known to excite the azimuthally symmetric $m = 0$ mode of helicon waves, was deformed in a long, highly stretched narrow loop. Therefore, the modified helicon discharge was excited in the magnetic field by a linear inductive antenna, consisted of two parallel conductors with counter-streaming RF currents, similar to a two-wire transmission line. The questions are whether it is possible to excite the discharge using such antenna and to obtain sufficient plasma uniformity along it.

1. EXPERIMENTAL SETUP 1

Preliminary experiments were performed in a quartz discharge chamber, of 14 cm in diameter and 40 cm long (Fig. 1). On the left end the quartz tube was closed with a metal flange, the opposite end was attached to a metal chamber of the same diameter, through which the system was pumped out. On the upper side wall along the quartz cylinder the linear antenna 30 cm long and 3 cm in width was placed. Transversal to the axis magnetic field was created by a rectangular electromagnet coil placed underneath the quartz chamber, close to it, or by a flat set of permanent magnets. The schematic drought of the device is shown in Fig.1. The magnetic field was divergent in vertical direction and in case of the electromagnet use the field decreased from 0.3 mT/A in the coil region to 0.1 mT/A near the antenna. Inside the chamber, along its bottom a grounded stainless strip of 8 cm in width was placed which imitated action of the wafer-holder in a technological device (not shown see in Fig. 1).

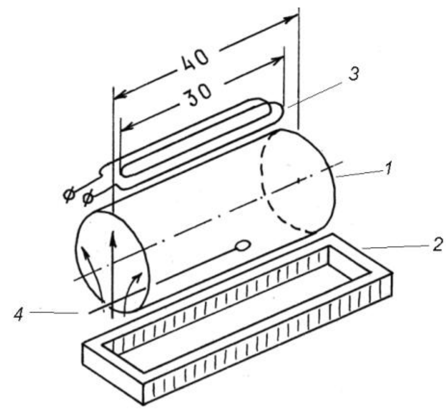

Fig. 1. Schematic diagram of experimental device with linear antenna upon quartz discharge chamber. 1 – quartz chamber 40 cm long and 14 cm in diameter; 2 − rectangular magnetic coil; 3 – two-turn linear antenna 30 cm long and 3 cm in width; 4 – movable flat Langmuir probe 12 cm below the antenna

Trough a conventional matching circuit the antenna was connected to the RF generator of frequency 13.56 MHz and output power up to 1 kW. Experiments were carried out in Argon gas at a pressure 0.65 Pa.

A flat Langmuir probe moved near the chamber bottom parallel to the axis at a distance of 12 cm from the inductive antenna. Distributions of ion saturation current to the probe, proportional to plasma density, were measured along the antenna.

2. PRELIMINARY PESULTS

The experimental results obtained using the coil and with use of the permanent magnet sets are shown in Fig. 2,a,b correspondingly. It was found that in both cases the linear antenna could produce a stable discharge of sufficient density, RF power was absorbed in plasma well enough and there existed some discharge regimes in which plasma density was approximately uniform along essential part of the antenna length.

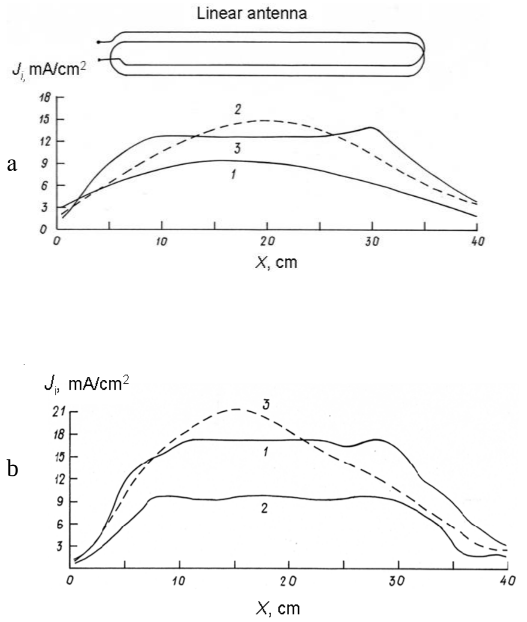

Fig. 2. Distributions of ion saturation current along the linear antenna; p_{Ar} = 0.65 Pa, W = 750 W.
a) Elektromagnet. Magnetic coil current: 1 – I = 0; 2 – I = 7 A; 3 – I = 20 A.
b) Permanent magnets. Magnetic field on the set's surface: 1 – B_0 = 63 mT; 2 – B_0 = 42 mT; 3 – B_0 = 0

It is seen that at certain conditions the ion current (and consequently the plasma density) is approximately constant on the distance of about 20 cm along the antenna. Some deviation of the density profile at X = 30 cm may be caused by proximity of the metal section and the magnetic field inhomogenity. At the same time any changes of discharge conditions led to loss of uniformity and in the most cases the density profile was not uniform.

3. EXPERIMENTAL DEVICE 2

Since in the quartz chamber the measurements were possible only along one coordinate, the subsequent experiments were performed in a metal discharge chamber of cubic shape with dimensions 22×22×20 cm. The two-turn linear antenna conductors passed through two quartz tubes of 16 mm diameter separated by 2 cm distance one from another in the upper part of discharge volume, at 5 cm below the top plane (Fig. 3). Three magnetic (or Langmuir) probes moved along mutually perpendicular directions, intersecting in the chamber center at 5 cm under the antenna (X – in parallel to the antenna and Z – along the external magnetic field). Uniform external magnetic field B_0 was created by two rectangular coils above and below the discharge chamber (not shown see in Fig. 3). The antenna plane was perpendicular to the external magnetic field lines.

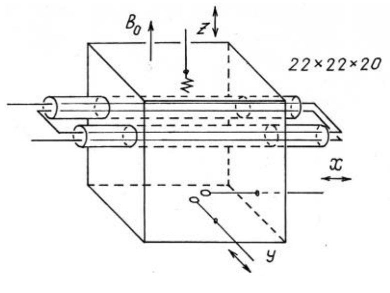

Fig. 3. Scheme of metal discharge chamber with the linear antenna immersed into plasma. The antenna conductors passed inside two quartz tubes at a distance of 5 cm below the upper plane of the chamber. Two rectangular magnetic coils – upper and lower – are not shown

The discharge volume was pumped out through an aperture, closed with the dense metal grid in the rear wall of the chamber.

4. RF FIELDS AND DENSITY DISTRIBUTIONS

It was found that increase of the magnetic field caused several step-like jumps in plasma density and ended with the full cease of discharge (Fig. 4). The critical magnetic fields corresponding to the density jump and to the discharge break down grow with increasing the RF power and gas pressure.

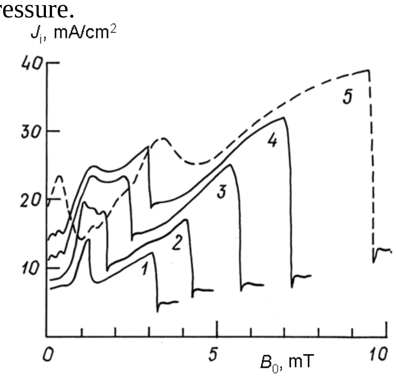

Fig. 4. Ion saturation current to the probe in the chamber center vs magnetic field. On curves 1-5 the RF power was gradually increasing from 180 to 750 W

After the discharge brake-down the reflected power highly increased, while the plasma density and absorbed power decreased. The final signals see in Fig. 4 are not the ion currents but the stray signals resulted from a strong breach of matching conditions. Thereupon the discharge may be restored only by decreasing of the magnetic field. This behavior is characteristic of the helicon discharge in a bounded volume at limited RF power and usually is connected with formation of the longitudinal standing helicon waves [3].

For measurements of spatial distributions of the wave RF magnetic fields the moveable magnetic probes were used. The probe tip represented itself 6-turn coil 8 mm in diameter from bare stainless wire of 0.3 mm diameter oriented to receive the component B_Z of RF magnetic field. After detecting the probe signal, proportional to amplitude of RF magnetic field, was registered by the *XY*-recorder. To *X* input of the recorder a voltage proportional to the probe position or to magnetic coil current (i.e. to the magnetic field strength) was applied. For phase measurements the reference signal was picked up by a small inductive loop situated near the antenna conductors. A continuously variable spiral delay line (0…0.25 μs) was used as a phase shifter.

Magnetic probe measurements revealed that along the external magnetic field (*Z*-axis) the standing waves really settled. Oscillations in every two adjacent maximums had the opposite phases. The standing wave patterns changed with the density jumps. With increasing the magnetic field B_0 the standing wave length also increased in accordance with the helicon waves' dispersion.

For plasma parameter measurements the *X*-probe was replaced with a flat Langmuir probe. But for relative estimations of spatial density distributions we used the ion saturation current to the bare magnetic probe, although its geometry was not defined.

Evidently, from measurements along only three mutually perpendicular axis it is not possible to fined out the whole three dimensional structure of the RF magnetic fields. As a rule, the spatial RF fields distributions are complicated and their phase relations are not too clear. Nevertheless, using the magnetic probes it was revealed that there existed two the most typical discharge states, differed one from another in standing waves structure and in density distributions along the linear antenna, which might be distinctly interpreted. Both the cases are shown in Fig. 5, a,b.

a

b

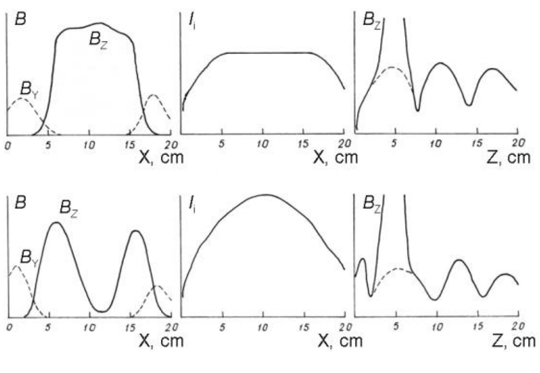

Fig. 5. Wave RF magnetic fields and ion saturation current spatial distributions. B_0 = 2.5 mT, p_{Ar} = 0,65 Pa. RF power: a) W = 640 W; b) W = 750 W

In the first regime (see Fig. 5,a) the wave RF magnetic field B_Z is approximately constant along the antenna, except for its ends. In this case the ion saturation current I_i (i.e. plasma density) also is highly homogeneous along the antenna (*X*-direction). B_Z distributions measured along *Z* (see Fig. 5) and along *Y* (Fig. 6, curve 1) axis, passing through the chamber center 5 cm below the antenna, in this case showed the third (odd) modes having the maximum amplitude in the center. The phase of oscillations changes to opposite one in every adjacent maximum. Note, that for small dimensions of the experimental device the uniform region is not large (10 cm see in Fig. 5). But the high degree of uniformity (often about 1 %) implies that the discharge "forgot" the boundary conditions on the antenna ends. This makes it possible that with increase the antenna length the uniformity will remain.

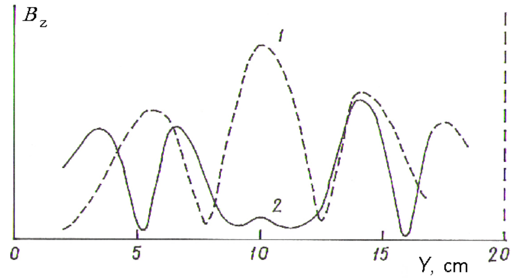

Fig. 6. Transversal distributions of RF magnetic fields. B_0 = 2.5 mT, p_{Ar} = 0.65 Pa; 1 – case (a) in Fig.5, W = 640 W; 2 – case (b), W = 750 W

Another discharge regime is shown in Fig. 5,b. In this case the B_Z amplitude has two maximums along the antenna, but *they are not components of standing wave*, because their phases are the same. Along the external magnetic field (*Z*-axis) the standing wave of fourth (even) mode is observed with zero field in the centre, while transversely to the antenna, along *Y* direction, (see Fig. 6, curve 2) we observe the 5-th (odd) mode, but *with absent the middle maximum*. In this case the density distribution along *X* is strongly nonuniform as it shows the curve $I_i(X)$ see in Fig. 5,b. These results demonstrate that even increasing the RF power can destroy the plasma uniformity. Generally, any changes in the discharge parameters – magnetic field, RF power, matching conditions or gas pressure – cause loss of the uniformity and, as a rule, the discharge with arbitrary chosen parameters has inhomogeneous density distribution. The exact conditions for obtaining the uniform density profile yet are not clear.

Plasma parameter measurements with the flat probe showed the electron temperature in the range of 2…4 eV. The plasma space potential was estimated from the ion energy distribution measured with a 5-grid retarding field energy analyzer and was found to be in the range of 15…20 eV. The ion current density at a distance of 10 cm from the linear antenna was about 20 mA/cm^2 that corresponded to plasma density 8×10^{11} cm^{-3}. These parameters are typical for the helicon discharges in Argon at given levels of RF power, pressure and magnetic field. So, the investigated discharge undoubtedly has the helicon nature.

The linear antenna originates from a deformed "planar" antenna. This antenna excites the azimuthally-symmetric mode of helicon waves $m = 0$ (m – the azimuthal number) by producing RF magnetic field B_Z

parallel to the external field B_0. Therefore, we may expect that the excited waves also are some modified helicon waves with prevailing longitudinal RF magnetic field B_Z, but with zero wave number along the antenna direction ($k_X = 0$).

Though the results of preliminary experiments in the quartz cylindrical chamber were rather hopeful, the possibility of uniform profile at much longer linear antenna has to be examined experimentally. Also the question is the uniformity of plasma flux on the grounded bottom of the chamber, where in technological device the treated surface will be situated, since in our experiments the uniform profiles were obtained only in between the antenna and the chamber bottom. These questions will be the matter of subsequent experiments.

CONCLUSIONS

In the presented work the possibility of discharge excitation by a linear antenna has been shown and the wave (helicon) nature of excited discharge was demonstrated. The existence of some regimes with uniform plasma density at essential part of the antenna length was revealed. Standing wave patterns corresponding to various discharge regimes were studied. At RF power of 1 kW on frequency 13.56 MHz, at Argon pressure 0.65 Pa and magnetic field 5 mT the ion current density of 20 mA/cm^2 was obtained that corresponded to plasma density of 8×10^{11} cm^{-3}.

A discharge system with the linear antenna immersed into plasma, that does not need a large area flat quartz window and is convenient for realization, is proposed. After increasing its dimensions and more detail study this type discharge may be used for design of technological equipment for uniform plasma treatment of large area products, including the flexible roll materials.

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МОДИФИЦИРОВАННЫЙ ГЕЛИКОННЫЙ РАЗРЯД, ВОЗБУЖДАЕМЫЙ ЛИНЕЙНОЙ ИНДУКЦИОННОЙ АНТЕННОЙ

А.Г. Борисенко, М.А. Белошенко, В.Ф. Вирко, Ю.В. Вирко, В.М. Слободян

Исследована новая разновидность геликонного разряда, способного генерировать линейно однородную плазму. Разряд возбуждается в магнитном поле индукционной антенной, состоящей из двух параллельных проводников с противофазными ВЧ-токами, подобно двухпроводной передающей линии. Продемонстрирована волновая природа разряда. Показано, что существуют некоторые разрядные условия, в которых плотность плазмы однородна на значительной части длины антенны. Предложена удобная в реализации разрядная система с линейной антенной, погружённой в плазму. При дальнейшем усовершенствовании такой разряд может быть использован для однородной плазменной обработки больших поверхностей.

МОДИФІКОВАНИЙ ГЕЛІКОННИЙ РОЗРЯД, ЗБУДЖУВАНИЙ ЛІНІЙНОЮ ІНДУКЦІЙНОЮ АНТЕНОЮ

А.Г. Борисенко, М.А. Бєлошенко, В.Ф. Вірко, Ю.В. Вірко, В.М. Слободян

Досліджено новий різновид геліконного розряду, здатного утворювати лінійно однорідну плазму. Розряд збуджується в магнітному полі індукційною антеною, що складається з двох паралельних провідників з протифазними ВЧ-струмами, подібно до двопровідної передавальної лінії. Продемонстровано хвильову природу розряду. Показано, що існують деякі розрядні умови, в яких густина плазми є однорідною на значній частині довжини антени. Запропонована зручна в реалізації розрядна система з лінійною антеною, зануреною в плазму. При подальшому удосконаленні такий розряд може бути використано для однорідної плазмової обробки великих поверхонь.