ICRF – VOLUME CHARGE – ANTENNA EDGE INTERACTIONS IN THE TORSATRONS U-3M AND U-2M

Part 1. FORMATION OF A VOLUME SPACE CHARGE (VSC) OF POSITIVE IONS

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A feature of fusion plasma rf discharges is the formation of near-wall volume-space charges (VSC) of positive ions. Nonlinear properties of VSC layers exert a determining influence on the rf discharge characteristics. The rf discharge includes the inductive and capacitive elements of the power input into the plasma, i.e. it is a hybrid discharge.

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INTRODUCTION

The ion cyclotron range of frequency (ICRF) waves has been routinely used in magnetic experiments for heating plasmas and driving current [1]. In the torsatrons Uragan-3M (U-3M) (l=3, m=9, R_0 =1 m major radius, $\bar{a} \approx 0.12$ m) and Uragan-2M (U-2M) (l=2, m=4, R_0=1.7 m, minor radius $\bar{a} \approx 0.24$ m) the plasma is produced and heated by the rf method under conditions when the current in HF-antennas is excited at frequency $\omega_{HF} \le \omega_{Bi}$ [2]. In U-3M and U-2M we have used the same rf generators Kaskad-1 (K-1) and Kaskad-2 (K-2) and similar systems for rf power supply into the plasma. The rf antennas were not provided with Faraday screens, separating and buffer protection devices. The plasma was generated and heated only using the rf methods on lower ion-cyclotron frequencies without any other preliminary ionization techniques [3]. The process of plasma production and confinement is determined by the power, frequency, rf field monochromaticity level, degree of rf system connection with plasma and by the basic plasma parameters. However, a main difference from the other heating methods is the formation in the low-pressure rf discharges of space-volume charges (VSC) of positive ions in the near-electrode or near-antenna regions [4]. VSC can consists of several layers with a thickness of the order of Debye radius and can possesses explicit nonlinear characteristics [5]. The power applied to the antenna in the rf discharges is from hundreds of kW to several MW. Such rf discharge conditions lead to strong edge ICRF-VSC-antenna surface interactions [6]. The interaction consequences determine, to a great extent, the processes in the plasma confinement volume and, in fact, characterize the rf discharge features. High voltages on the antennas and small VSC sizes complicate direct investigations of these interactions. On U-3M and U-2M (as on the most of plasma facilities) the edge plasma interactions were investigated indirectly, i.e. by their secondary effects. The experiments were of a diverse character. In the present paper we attempt to summarize and systematize the results of experimental works carried out on U-3M and U-2M with taking into account the data of nonlinear edge interaction observations on other plasma facilities. The paper includes three independent parts. The first part considers the physics of VSC formation and their main characteristics. The second part reports the results of investigations on the VSC-antenna interaction. The third part presents the mechanisms of ICRF-VSC interaction.

1. VSC FORMATION

As early as in 1957 S.M. Levitsky has noted that the energy of ions accelerated in the alternating electric field is insufficient for the recorded strong sputtering of electrodes in the rf discharges [4].

This author has assumed that ions can gain the energy sufficient for strong sputtering in the direct-current electric field. Such field can be formed by VSC of positive ions. Also he has proposed an enough simple mechanism of VSC formation. Under the action of the rf field $E = E_m \cos \omega t$ the electron are moving and oscillating with amplitude $A = \mu_0 \cdot ({E_m}/{p\omega})$, where μ_0 – mobility of electrons at p=133.3 Pa. During the immediate rf field period the electrons reach the electrode surface when they are in their mid position (at ωt=0. π) at a distance less than the amplitude A distance from the electrode surface. The drift mobility μ_0 of ions is less by two orders of magnitude than that of electrons and therefore their displacement during the rf field period is insignificant. So, in the near-electrode region (in the near-antenna region in the case of U-3M and U-2M torsatrons) an excess of positive ions takes place, it means that the VSC of positive ions is formed. The quasi-constant electric field, generated by volume charges, ejects the ions from the discharge to the antenna and accelerates them up to sufficiently high energies thus increasing the physical sputtering of the antenna surface. The energy for this acceleration arrives from the rf circuit and appears as a power dissipation. The VSC-

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produced potential also tends to keep the electrons from escape to the antenna. So, the plasma, similarly to any other system having a tendency to the self-preservation, forms a perfect process for the quasi-neutrality retrieval.

The mechanism of VSC formation in the low-pressure rf discharges proposed by S.M. Levitsky was proved in experiments and calculations [4, 7], and in V.A. Godyak's opinion (a known specialists in the field of rf discharges) this mechanism has become a commonly accepted one [8].

In gas discharges, due to the difference in the coefficients of different-sign charge carrier diffusion, VSC arises also near the walls and internal elements of the plasma equipment (limiters, diagnostic devices, torsatron winding covers in U-3M) [9]. In the torsatrons U-3M and U-2M the VSC formation has been observed in the near-antenna region where the rf field value is maximum, and, naturally, the VSC effect on the plasma is the most significant.

As a rule VSC consists of a few layers [5, 10]. The region where the electric field is concentrated is named a double layer. In the double layer the charge particles are moving under the electric field action without collisions, i.e. the mean free path of the particles exceeds the thickness of the double layer. Near the electrodes the thickness of each of layers can change in the alternating electric field, but their total thickness $\delta \approx (V/4\pi en)^{1/2}$ [8] remains constant and equals to the doubled amplitude of electron oscillations [11].

The layers of uncompensated VSC have a pronounced nonlinear volt-ampere characteristic (VAC) [8]. Really the nonlinear properties of near-antenna VSC layers determine many nonlinear interactions in the edge plasma of U-3M and U-2M. These results are reported in the second and third parts of the present paper.

2. HYBRID RF DISCHARGE

The formation of VSC begins when the electrons go off from the near-antenna region to its surface. Thus, the closest near-antenna region turns out the electron-depleted one. Behind VSC the plasma remains as a quasi-neutral one. However, due to the positively-charged near-antenna region the plasma in the whole becomes positively charged relatively to the antenna [11]. A capacitive antenna-plasma coupling component transforms the discharge in the hybrid one [1]. The conduction current, flowing in the quasi-neutral plasma in this case, circuites in the electrode region with a displacement current [11]:

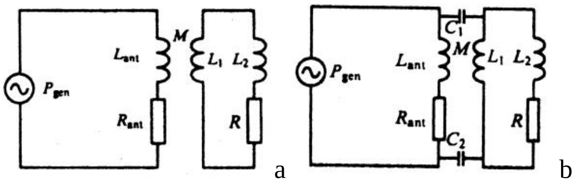
$$div[e(\mu_e n_e + \mu_i n_i)\vec{E} + \frac{1}{4\pi}\frac{d\vec{E}}{dt}] = 0.$$

It means that the rf power supply to the plasma can be performed by both the inductive channel and the capacitive channel. The equivalent circuit of the rf-discharge in the case of its purely inductive excitation is shown in Figure, a [12].

The rf generator is connected in series with the ohmic resistance and antenna inductance, as well as, with the equivalent resistance and plasma inductance.

In such representation of the discharge circuit the RF-generator power P_{gen} is related with the power P_{ant} released in the antenna and the power P_{pl} released in the plasma by expression $P_{gen} = P_{ant} + P_{pl}$ or P_{gen} $= \frac{1}{2} I^2 (R_{ant} + R_{pl})$. Here I is the current passing through the antenna, R_{ant} - active antenna resistance, R_{pl} - equivalent plasma resistance. When the load is matched with the generator, the active RF power P_{gen} is distributed between two channels for antenna heating and the other part is absorbed by the plasma. In reality, such idealized inductive RF discharge does not exist.

Above it has been shown that the pulse applied to the antenna causes the positive-ion VSC formation in the near-antenna region. The plasma becomes a positively charged relatively to antenna. In fact there is formed a capacity between the antenna and the plasma. The presence of the capacitive coupling between the antenna and the plasma signifies that in the torsatrons U-3M and U-2M a hybrid discharge arises. The equivalent circuit of such a discharge is presented in Figure, b.



Equivalent circuits of rf discharges: (a) purely inductive rf discharge; (b) hybrid rf discharge

Despite the conventionality of the represented circuit it gives a notion about the circuitry determining the rf discharge. Here the plasma is represented as active R and reactive L_1 and L_2 loads. They are connected both in the inductive and capacitive discharge circuits. The rf power from the generator is distributed to the antenna heating, to the plasma heating with induction current, to the plasma heating by passing the current through the circuit comprising capacity C_1, capacity C_2 and plasma ohmic resistance R. The values of capacities C_1 and C_2 are determined, in fact, by the antenna area (as the plasma is the second capacitor plate), and by the distance between the antenna surface and plasma. The resistance R is determined by the ohmic plasma resistance. The appreciation of the role of components in the rf circuit and in the plasma is enough difficult. In the case of a hybrid discharge the rf generator power change leads to the change of both the plasma parameters and fractions of the power contributed into the plasma via the capacitive and inductive channels.

CONCLUSIONS

The paper presents the physical fundamentals of VSC formation in low-pressure rf discharges. In fact VSC produces a hybrid discharge comprising the inductive and capacitive channels. As a result, the rf power contribution is distributed between the rf system components and the plasma.

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КРАЕВЫЕ ВЗАИМОДЕЙСТВИЯ ICRF – ОБЪЁМНЫЙ ЗАРЯД – АНТЕННА В ТОРСАТРОНАХ У-3М И У-2М
ЧАСТЬ 1. ОБРАЗОВАНИЕ ОБЪЁМНОГО ПРОСТРАНСТВЕННОГО ЗАРЯДА (ОПЗ) ПОЛОЖИТЕЛЬНЫХ ИОНОВ

В.Л. Бережный

Особенностью ВЧ-разрядов термоядерной плазмы является образование пристеночных объёмных пространственных зарядов (ОПЗ) положительных ионов. Нелинейные свойства слоёв ОПЗ оказывают определяющее влияние на характеристики ВЧ-разрядов. ВЧ-разряд включает индуктивную и ёмкостную компоненты ввода мощности в плазму, т.е. является гибридным разрядом.

КРАЙОВІ ВЗАЄМОДІЇ ICRF – ОБ’ЄМНИЙ ЗАРЯД – АНТЕНА В ТОРСАТРОНАХ У-3М ТА У-2М
ЧАСТИНА 1. СТВОРЕННЯ ОБ’ЄМНОГО ПРОСТОРОВОГО ЗАРЯДУ (ОПЗ) ПОЗИТИВНИХ ІОНІВ

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Особливістю ВЧ-розрядів термоядерної плазми є створення пристіночних об’ємних просторових зарядів (ОПЗ) позитивних іонів. Нелінійні властивості шарів ОПЗ чинять значущий вплив на характеристики ВЧ-розрядів. ВЧ-розряд включає індуктивну та ємнісну компоненти введення потужності в плазму, тобто є гібридним розрядом.