INFLUENCE OF THE FRAME-TYPE ANTENNA ON THE RF-DISCHARGE PERIPHERAL PLASMA PARAMETERS IN THE URAGAN-3M TORSATRON

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A qualitative evaluation is made of what changes of the electric potential near the frame-type antenna occur under the influence of following effects: the ponderomotive Miller force, which acts on plasma electrons near the source of radiation; the rectification of the probe oscillating potential of the RF waves, which are excited by the frame-type antenna; and the rectified potential of the antenna, which arises, when RF power is on.

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INTRODUCTION

In the $l = 3$, $m = 9$ Uragan-3M (U-3M) torsatron with an open helical divertor, a hydrogen plasma is produced and heated by RF fields with using an unshielded frame-type (FT) antenna.

It is known that far away from the antenna, the potential, which is induced in the peripheral plasma by the RF antenna, is small. This potential does not affect noticeably plasma parameters. However, near the antenna essential variations of the potential and the temperature and density of electrons were revealed.

Specifics of probe measurements in the magnetic field have been investigated earlier in many works, e.g., [1, 2]. The analysis of RF-field and -current rectification effects on the nonlinear conductivity of spatial charge layers in low-pressure RF-discharges is described in [3, 4].

The microscopic theory of average forces acting on a plasma in strong fields of electromagnetic radiation was presented in [5]. This theory was based on the motion equations of plasma electrons.

This report deals with a qualitative evaluation of the ponderomotive potential effect on the readings of a Langmuir probe in the case, when it is located near to the FT antenna. This potential is created by the antenna electromagnetic radiation.

EXPERIMENTAL CONDITIONS

U-3M is a 'classical' $l/m = 3/9$ torsatron with the natural separatrix forming a helical divertor. The major and average plasma radii are $R_0 = 100$ cm and $\bar{a} \approx 12$ cm; the toroidal magnetic field $B_\varphi \approx 0.7$ T is produced by the helical coils only, the rotational transform on the plasma boundary is $i(a)/2\pi \approx 0.3$. The whole magnetic system is placed inside a large, 5m-diameter vacuum tank, its volume being ~ 200 times as large as the confinement volume. With a continuous hydrogen inlet at a pressure of $p \approx 10^{-5}$ Torr, a currentless plasma is produced and heated by RF-fields in the Alfvén range of frequencies, $\omega \le \omega_{ci}$ (ω and ω_{ci} are the generator and ion-cyclotron frequencies), by using two types of unshielded antennas twisted along the helical windings: the FT antenna and the three-half-turn (THT) antenna (Fig. 1).

The FT antenna (Fig. 2) is located on the outside of the plasma column. The antenna lead-ins are in the symmetrical poloidal cross-section of the torus D1 between the helical windings I и III (see Fig. 1).

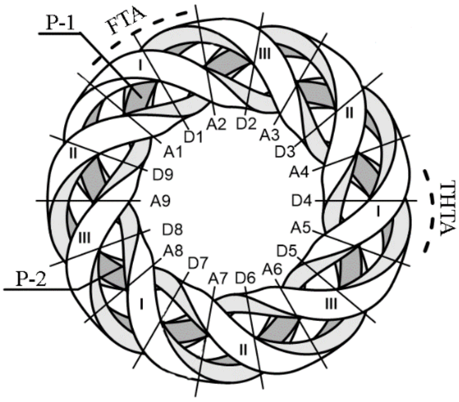

Fig. 1. Helical windings I, II, III of the U-3M magnetic field. Noted are symmetrical poloidal sections A1, D1, A2, D2, …, A9, D9 in helical field periods 1, 2, …, 9, respectively, and locations of movable Langmuir probes P-1 и P-2, as well as locations of the frame-type (FTA) and three-half-turn (THTA) antennas along the torus (dashed lines). The antenna lead-ins are on the outer side of the torus between windings I и III in sections D1 (FTA) и D4 (THTA)

Fig. 2. Frame-type antenna and its location with respect to the helical windings

A pair of antenna conductors, oriented along the magnetic field, excites the slow wave. The maximum of generation is observed near $l = 11$, where l is the toroidal wave harmonic. Three conductors oriented in the poloidal direction excite predominantly the fast wave. In this case, the maxima of generation correspond to $l = 8,...11,\ 26$ [6].

Fig. 3 shows the probe $I(V)$ characteristics for the cases, where the electric probe is located (a) far from the antenna (probe P-1) and (b) at a distance of 3 cm from it (probe P-2, see Fig. 1). The difference between floating potentials is $\delta\varphi_f \approx -150$ V.

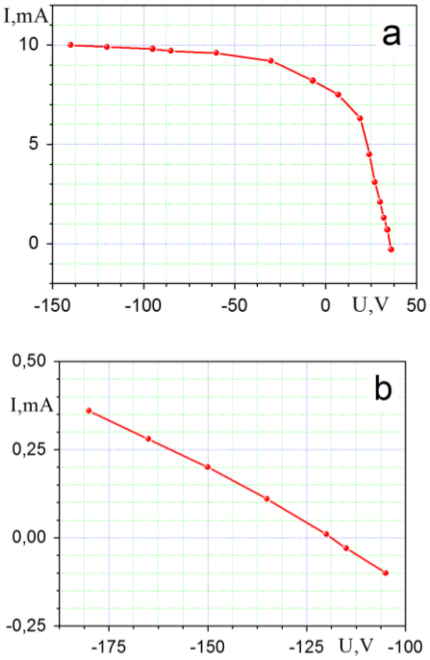

Fig. 3. Examples of electrical probe current-voltage characteristics measured in regimes (a) away from the antenna (probe P-2) and (b) near the antenna (probe P-1)

Further, we evaluate three effects that could affect the floating potential of the probe in the plasma outside of the confinement region. For these evaluations we use next parameter points: $n_e = 10^{10}\ \text{cm}^{-3}$, $T_e = 50\ \text{eV}$, $T_i = 10\ \text{eV}$, $\omega = 5.5\cdot10^7\ \text{s}^{-1}$.

OSCILLATING POTENTIAL OF THE RF WAVES

Let us evaluate the probe rectification of the oscillating potential of RF waves, which are excited by the FT antenna.

Using the dispersion equation

$$(N^2\delta_{ij} - N_iN_j - \varepsilon_{ij})E_j = 0\,, \qquad (1)$$

we find a relation between the electromagnetic field components

$$\frac{E_x}{\Delta_x} = \frac{E_y}{\Delta_y} = \frac{E_z}{\Delta_z}\,, \qquad (2)$$

where

$$\Delta_x = (N^2 - \varepsilon_3)N_xN_y + i\varepsilon_2(N_x^2 + N_y^2)\,, \qquad (3)$$

$$\Delta_y = N^2N_y^2 - \varepsilon_3(N_z^2 + N_y^2) - \varepsilon_1(N_x^2 + N_y^2)\,, \qquad (4)$$

$$\Delta_z = ((N^2 - \varepsilon_1)N_y + i\varepsilon_2N_x)N_z\,, \qquad (5)$$

ε_{ij} is the plasma dielectric tensor, ε_1, ε_2 and ε_3 are this tensor components, N is the wave refractive index, $N_{x,y,z}$ are this refractive index components, δ_{ij} is a Kronecker symbol.

From the Maxwell equations, using conditions

$$\vec E = -\nabla\varphi - \frac{1}{c}\frac{\partial}{\partial t}\vec A,\ div\vec A = -\frac{1}{c}\frac{\partial}{\partial t}\frac{\varepsilon_{ij}N_iN_j}{N^2}\varphi\,, \qquad (6)$$

where $\vec E$, φ, $\vec A$ are electric field, scalar and vector potentials of the electromagnetic wave, we find the expression for oscillating potential amplitude of the wave

$$\varphi = -\frac{cN^2}{\omega}\frac{i\vec N\vec E}{N^4 - (\varepsilon_1N_\perp^2 + \varepsilon_3N_\parallel^2)}\,, \qquad (7)$$

where $N_{\perp,\parallel} = k_{\perp,\parallel}c/\omega$ are the wave refractive indexes, which are perpendicular and parallel with respect to the external magnetic field.

At first, we evaluate the oscillating potential amplitude of the slow wave, which is excited mainly by the FT antenna conductors which are parallel with respect to the external magnetic field. The dispersion equation of the slow wave can be written as

$$D = k_{\perp|}^2 + \frac{\varepsilon_3}{\varepsilon_1}k_\parallel^2\,, \qquad (8)$$

or

$$D = k_{\perp|}^2 + \frac{m_i}{m_e}\frac{\omega^2 - \omega_{ci}^2}{\omega^2}k_\parallel^2\,. \qquad (9)$$

As is well known, the wave energy propagates along the group velocity direction

$$\vec v_g = \frac{\partial\omega}{\partial\vec k} = -\frac{\partial D/\partial\vec k}{\partial D/\partial\omega}\,. \qquad (10)$$

Then we find

$$\vec v_{g\parallel} = \frac{\omega_{ci}^2 - \omega^2}{\omega_{ci}^2}\frac{\omega}{k_\parallel}\,,\ \vec v_{g\perp} = -\sqrt{\frac{m_e}{m_i}}\frac{\omega^2}{\omega_{ci}^2}\frac{\sqrt{\omega_{ci}^2 - \omega^2}}{k_\parallel}\,. \qquad (11)$$

Thus, $\left|v_{g\perp}/v_{g\parallel}\right| = \sqrt{m_e/m_i} << 1$ and the wave propagates in general along the magnetic force line, weakly displacing from the magnetic surfaces, which are crossed by the longitudinal conductor, that excites the wave. As shown in [7], the slow wave decays along the force line on distances of the order of antenna length and so does not achieve the probe P-1.

Now we evaluate the oscillating potential amplitude of the fast wave, which is excited by the transversal FT antenna conductors with respect to the external magnetic field.

Thus, using expressions (2), (11) and dispersion equation

$$N_{\perp F}^2 = ((\varepsilon_1 - N_\parallel^2)^2 - \varepsilon_2^2)/(\varepsilon_1 - N_\parallel^2)\,, \qquad (12)$$

from (7) we find the expression for oscillating potential amplitude in the case $N_y = 0$:

$$\varphi \approx i\frac{c\varepsilon_2^2N^4|N_x|}{\omega\varepsilon_3^2N_\parallel^4}E_ye^{-|k_x|\Delta x}\,. \qquad (13)$$

The rectified potential of the fast wave is small on the distance $\Delta x \approx 3\,\text{cm}$ from the antenna [4] $\delta\varphi \approx \varphi/2 \le 10^{-8}$ V for $l = 5...20$.

Thus, rectified by the probe oscillating potential of the RF fields, which are excited by the FT antenna, do not essentially affect the probe indications.

RECTIFIED POTENTIAL OF THE ANTENNA

Now we evaluate the rectified FT antenna potential, which arises, when RF power is on [3, 4]. The measured direct potential is shown in the Fig. 4.

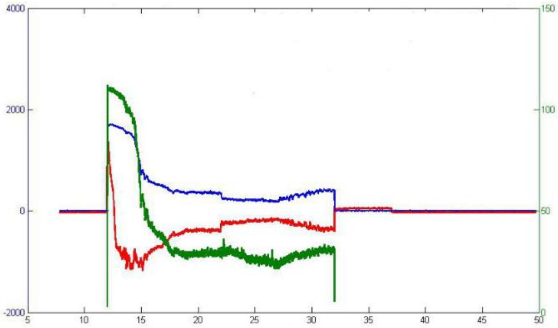

Fig. 4. The measured dependences of direct potential (red, V), ac voltage (blue, V) and current (green, A) amplitudes on the frame-type antenna from time (ms)

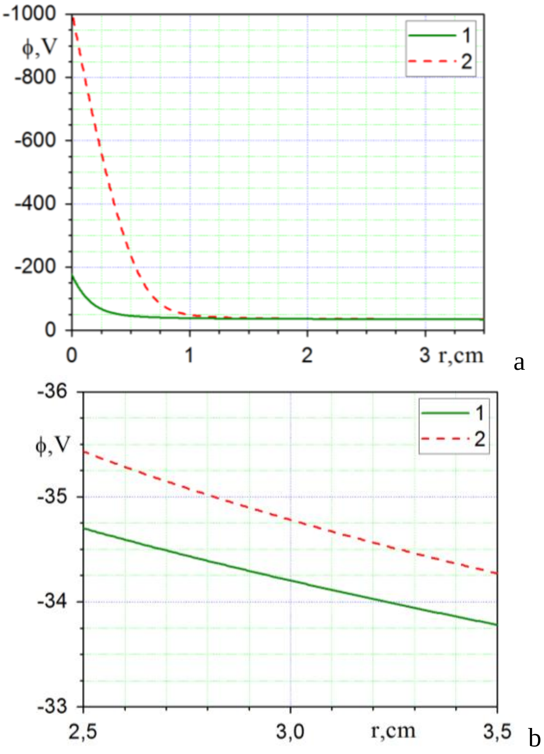

Fig. 5. The potential distribution near the antenna (a), when RF power is off (1) and when the rectified frame-type antenna potential is equal to 1кV (2) and the same dependences on a smaller scale (b)

As can be seen from Fig. 4, when the RF voltage $\lesssim 2$ кV is applied to the antenna, it is charged up to $\lesssim 1$ кV of the d.c. potential.

To evaluate the effect of the rectified potential of the FT antenna on the probe indications, we use the gas-dynamic motion equation and continuity equation for ions in conjunction with Poisson equation in the absence of external magnetic field taking into account ionization and charge exchange processes.

$$\frac{\mathrm{v}_i^{2}{}'}{2} = -\frac{e\varphi'}{m_i} - \nu_i\,\mathrm{v}_i - \frac{T_i}{m_i}\frac{n_i'}{n_i}, \qquad (14)$$

$$(n_i \mathrm{v}_i)' = \alpha n_e , \qquad (15)$$

$$\varphi'' = 4\pi e(n_0 e^{e\varphi/T_e} - n_i), \qquad (16)$$

where v, n, T, m, ν are the ion or electron hydrodynamic velocity, density, temperature, mass, and effective collision frequency according to the inferior index, *e* is the elementary charge, φ is the self-consistent field potential, α is the ionization frequency, the derivative with respect to *x* is primed ʹ.

The system of equations (14-16) is solved numerically.

The potential distribution near the antenna in different scales is shown in Fig. 5 for the cases, where RF power is off and when the rectified FT antenna potential is equal to 1кV. In these calculations the antenna is modeled as an infinite cylindrical conductor with a radius of 1 cm.

As may be seen from Fig. 5, the antenna potential is screened by plasma. When it increases from 200 V up to 1 кV, the plasma potential is changed by ~ 1 V at the distance $\Delta x \approx 3$ cm from the antenna.

So, the FA antenna rectified potential does not affect the probe measurements.

MILLER FORCE

The Miller force acts on plasma particles near the source of electromagnetic radiation as [8]

$$\vec{F} = -\frac{q^2}{4m\omega^2}\nabla\left|\vec{E}_0\right|^2 , \qquad (17)$$

where $\vec{E}_0$ is the RF electric field amplitude near the radiation source, *q* and *m* are the charge and mass of the particle. The action of this force on the ions can be neglected ($m_i >> m_e$).

The Miller's strength is always directed against the gradient of the electromagnetic wave amplitude, and acting on the electrons, "squeezes" them from the region near the radiation source.

Expression (17) can be rewritten as:

$$\vec{F} = -\nabla\varphi_p , \qquad (18)$$

where $\varphi_p = (q^2/(4m\omega^2))\left|\vec{E}_0\right|^2$ is the ponderomotive potential.

To find the ponderomotive potential at a distance *r* from the antenna, we assume that the wave field amplitude oscillates in the toroidal direction and depends on *r* as $E_0 \sim e^{i(l\varphi + k_\perp r)}$. As the peripheral plasma density is low ($n_e \lesssim 10^{11}$ cm^{-3}), then $N^2 = N_\perp^2 + N_\parallel^2 \approx 1$. Taking into account $N_\parallel^2 >> 1$, we find

$$N_\perp^2 \approx -N_\parallel^2 , \qquad (19)$$

where $N_{\perp,\parallel} = k_{\perp,\parallel} c/\omega$ are the wave refractive indices in parallel and perpendicular directions with respect to the external magnetic field, $k_{||} = l/R_0$. The wave vector component $k_\perp \approx il/R_0$ determines damping of the wave amplitude and the ponderomotive potential towards inhomogeneity:

$$\varphi_p = \frac{e^2}{4m_e\omega^2}\left|\vec{E}_0(r=0)\right|^2 e^{-2|k_\perp|r}. \qquad (20)$$

The Miller force changes the electrical potential near the FT antenna by the value

$$\delta\varphi = -\frac{\varphi_p}{e} = \frac{e}{4m_e\omega^2}\left|\vec{E}_0(r=0)\right|^2 e^{-2|k_\perp|r}. \qquad (21)$$

The dependence of the plasma electric potential change at a distance of 3 cm from the antenna due to Miller force action $\delta\varphi$ as a function of the toroidal wave number *l* is shown in Fig. 6.

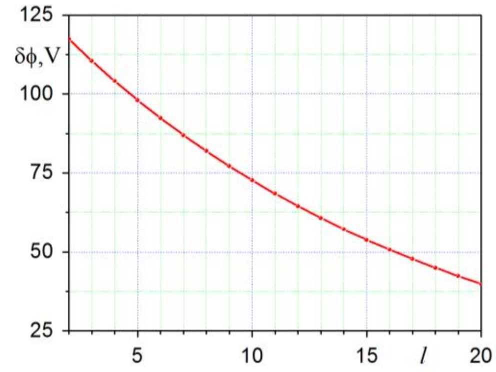

Fig. 6. The plasma electric potential change $\delta\varphi$ due to Miller force action at a distance of 3 cm from the antenna vs the toroidal wave number

As can be seen from Fig. 6, the magnitude of the plasma electric potential change is of the same order as the floating potential difference $\delta\varphi_f$ in the case of measuring away from the antenna and at a distance of 3 cm from it.

CONCLUSIONS

Qualitative evaluations of the electric potential changing $\delta\varphi$ near the frame-type antenna under the Miller force action are received.

The value of $\delta\varphi$ is of the same order of magnitude as the floating potential difference $\delta\varphi_f$ in the case of measuring away from the antenna and at a distance of 3 cm from it for typical values of the toroidal wave number $l = 5...20$.

So, the Miller force action near the FT antenna is the reason for appearance of this difference.

The results of this work give a better understanding and further inquiry of processes which take place in the Uragan-3M torsatron in close proximity to the FT antenna.

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ВЛИЯНИЕ РАМОЧНОЙ АНТЕННЫ НА ПАРАМЕТРЫ ПЕРИФЕРИЙНОЙ ПЛАЗМЫ ВЧ-РАЗРЯДА В ТОРСАТРОНЕ УРАГАН-3М

Я.Ф. Лелеко, Л.И. Григорьева, В.В. Чечкин, Д.Л. Греков

Получены качественные оценки изменения электрического потенциала вблизи рамочной антенны вследствие воздействия: пондеромоторной силы Миллера, которая действует на электроны плазмы вблизи источника излучения; выпрямленного зондом осциллирующего потенциала высокочастотных волн, возбуждаемых рамочной антенной; и выпрямленного потенциала рамочной антенны, возникающего при подаче на неё ВЧ-напряжения.

ВПЛИВ РАМКОВОЇ АНТЕНИ НА ПАРАМЕТРИ ПЕРИФЕРІЙНОЇ ПЛАЗМИ ВЧ-РОЗРЯДУ В ТОРСАТРОНІ УРАГАН-3М

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Отримані якісні оцінки зміни електричного потенціалу поблизу рамкової антени внаслідок впливу: пондеромоторної сили Міллера, яка діє на електрони плазми поблизу джерела випромінювання; випрямленого зондом осцилюючого потенціалу високочастотних хвиль, які збуджуються рамочною антеною; випрямленого потенціалу рамочної антени, який виникає при подачі на неї ВЧ-напруги.