THE HF FIELD PATTERN IN THE MAGNETIZED PLASMA CYLINDER OF FINFTE LENGHT

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The PR-1 device is the wide-aperture source of homogeneous plasma. It is using for plasma processing of big diameter samples such as parts of HF antenna and elements of vessel of fusion devices. The paper presented deals with investigation of HF field pattern of the operation regime with external magnetic field. It is shown that the HF fields penetrate into the plasma volume better as compared with the case when magnetic field is turned off. So the plasma flow of greater density could be generated.
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INTRODUCTION

The device PR-1 represents the wide-aperture homogeneous plasma source intended for processing of the pattern in diameter more than 30 cm. It can be the component of the high-frequency (HF) antenna of the thermonuclear traps, elements of the chambers coating of the installations etc. The theoretical and experimental research of the plasma creation in this installation by HF fields with frequency f=13.56 MHz was carried out earlier [1,2] in operational modes without external magnetic field. The presence of the solenoid allows to carry out the experiments with external axial magnetic field B about 100 Gs. The present activity is devoted to investigation the influence of the external magnetic field value on the HF field spatial distribution in device volume. It is allows to make the conclusion about uniformity of spatial distribution of HF field in the plasma and about the possibility of using the external magnetic field for regimes of the work of the device PR-1 with greater plasma density.

The framework of the device PR-1 is the metal cylinder of radius $a = 22.5$ cm and altitude l < a. The dielectric plate (I) with width g and permittivity ε_d is stacked on the cylinder bottom and separates the antenna from the chamber bottom. The antenna is covered with dielectric plate (II) with width $h-g$ and permittivity ε_d.

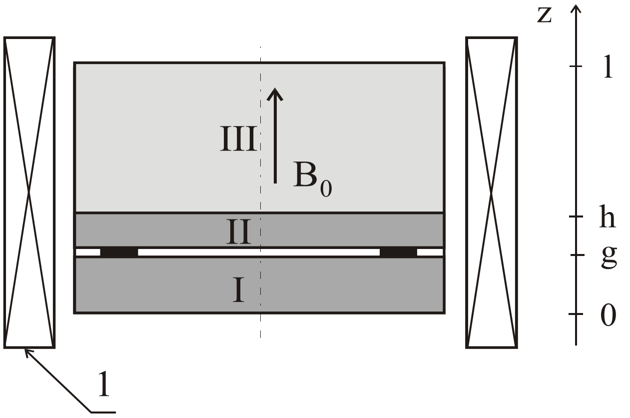

Fig.1. The cross-section of the device PR-1 along the cylindrical chamber axis. The antenna is located between dielectric plate (I) and (II). The plasma occupies the region (III), 1 – the solenoid for creating the external magnetic field

The plasma is formed in region (III), having the altitude l-h along the chamber axis (axes Z in further consideration). Accordingly the experiment [2], the plasma in the region (III) is uniform. Therefore at the further consideration will be used the model of the homogeneous plasma cylinder.

THE BASIC EQUATIONS

Let us to study the spatial distribution of HF fields exited by the generator with frequency f=13.56 MHz. We accept that the external magnetic field value is equal to 100 Gs. In this case the field frequency $\omega = 2\pi f$ located in interval $\omega_{LH} < \omega << \omega_{ce}$, where ω_{LH} is low hybrid frequency, ω_{ce} is electron cyclotron frequency. In an effective range of pressure of neutral gas ($p = 5\cdot 10^{-2} \div 7\cdot 10^{-4} Topp$) the inequalities $\nu_{eff} << \nu_a << \omega$ (ν_{eff} is the effective collisions frequency of electrons with ions, ν_a is the frequency of elastic collisions of electrons with atoms) are executed. Therefore we neglected the collisions in plasma permittivity tensor. The components of the tensor permittivity are:

$$\varepsilon_1 = 1 - \omega_{pi}^2/\omega^2 + \omega_{pe}^2/\omega_{ce}^2,$$

$$\varepsilon_2 = -\omega_{pe}^2/\omega\omega_{ce},\ \varepsilon_3 = 1 - \omega_{pe}^2/\omega^2,$$

where ω_{pi} and ω_{pe} are the ions and electrons plasma frequencies. We assume that the relation of a HF of fields to azimuth coordinate φ looks like $\exp(im\varphi)$ and from axial coordinate z is $\exp(k_{\|}z)$, where $k_{\|}$ is longitudinal component of the wave vector in relation to the external magnetic field. From the Maxwell equations can be obtained the system of related equations described the behaviour of the HF fields in plasma

$$(\varepsilon_1 + N_{\|}^2)\left[\frac{1}{r}\frac{d}{dr}\left(r\frac{d}{dr}\right) - \frac{m^2}{r^2}\right]B_z +$$
$$\frac{\omega^2}{c^2}\left[(\varepsilon_1 + N_{\|}^2)^2 - \varepsilon_2^2\right]B_z - \qquad ,$$
$$N_{\|}\varepsilon_2\left[\frac{1}{r}\frac{d}{dr}\left(r\frac{d}{dr}\right) - \frac{m^2}{r^2}\right]E_z = 0$$

$$N_{\|}\varepsilon_2\left[\frac{1}{r}\frac{d}{dr}\left(r\frac{d}{dr}\right)-\frac{m^2}{r^2}\right]B_z+$$
$$\left[\varepsilon_1(\varepsilon_1+N_{\|}^2)-\varepsilon_2^2\right]\left[\frac{1}{r}\frac{d}{dr}\left(r\frac{d}{dr}\right)-\frac{m^2}{r^2}\right]E_z+ \quad (1)$$
$$+\frac{\omega^2}{c^2}\varepsilon_3\left[(\varepsilon_1+N_{\|}^2)^2-\varepsilon_2^2\right]E_z=0$$

($N_{\|}=k_{\|}c/\omega$). The solutions of this system are $B_z=BZ_m(N_{\perp F}x)$ and $E_z=CZ_m(N_{\perp S}x)$. Here $Z_m(x)$ are the cylindrical functions that are finite at $x=0$, $x=r\omega/c$. By an index F is denote the smaller on absolute value and index S is denote the greater radial index of refraction, which are determined by equation:

$$N_{F,S}^2=\frac{1}{2\varepsilon_1}\left[\begin{array}{l}\varepsilon_2^2-(\varepsilon_1+\varepsilon_3)(\varepsilon_1+N_{\|}^2)\pm\\ \left[\begin{array}{l}[\varepsilon_2^2-(\varepsilon_1+\varepsilon_3)(\varepsilon_1+N_{\|}^2)]^2-\\ -4\varepsilon_1\varepsilon_3[(\varepsilon_1+N_{\|}^2)^2-\varepsilon_2^2]\end{array}\right]^{1/2}\end{array}\right] \quad (2)$$

We will to note the oscillations with N_S the as F-mode, and the oscillation with N_S as S-mode.

Fig.2. The dependence of radial refraction parameters $N_{\perp}^2$ of the F-mode and S-mode on $N_{\|}^2$

As can see from fig.2 depending on $N_{\|}^2$ one of modes can be surface (on radius), and second propagating (zone I, IV); both modes can be propagating on radius (zone II), or surface (zone III). Thus each of modes has all three components (r, j, z) both magnetic and electrical field. As $E_z\sim Z_m(x)$, and $E_\varphi\sim\alpha\, Z_m(x)+\beta\, Z'_m(x)$ ($Z'_m(x)=dZ_m(x)/dx$), the fulfillment of the boundary conditions on the device lateral $E_\varphi\big|_{r=a}=0$ and $E_z\big|_{r=a}=0$ is possible only for a superposition of modes. Let's write E_z of the F-modes as $E_z=k_F\partial B_z/\partial z$, and B_z of the S-modes as $B_z=k_S\partial E_z/\partial z$. The obvious kind of the factors k_F and k_S can be easy finding from equations (1). From conditions on a lateral wall can be obtained the following transcendental equation:

$$\left[\begin{array}{l}\varepsilon_2\dfrac{m}{a'}Z_m(N_Fa')+\\ N_FZ'_m(N_Fa')\left(\varepsilon_1+N_{\|}^2-\varepsilon_2k_FN_{\|}^2\right)\end{array}\right]Z_m(N_Sa')-$$
$$-N_{\|}^2k_FZ_m(N_Fa')\left\{\begin{array}{l}\varepsilon_2\dfrac{m}{a'}k_SZ_m(N_Sa')+\\ N_SZ'_m(N_Sa')\left[k_S\left(\varepsilon_1+N_{\|}^2\right)-\varepsilon_2\right]\end{array}\right\}=0 \quad , (3)$$

where $a'=a\omega/c$. This equation determines the row of values $N_{\|q}^2,\ q=1,2\ldots\infty$, which are excited in plasma. The appropriate values of N_{Fq} and N_{Sq} can be obtained from equation (2). The obvious kind of the dependence of the plasma fields on z is determined by boundary conditions $E_r(r)=0$ and $E_\varphi(r)=0$ on the chamber back at $z=1$. From them follows: $E_z\sim\cos[N_{\|q}(l-z)]$ (or $E_z\sim ch[N_{\|q}(l-z)]$) and $B_z\sim\sin[N_{\|q}(l-z)]$ (or $B_z\sim sh[N_{\|q}(l-z)]$). Thus, the general solution for m-th harmonics of the HF field in plasma can be written as

$$E_{zm}=\sum_{q=1}^{\infty}C_q\cos[N_{\|q}(l-z)][k_{Fq}Z_m(N_{Fq}x)+Z_m(N_{Sq}x)] \quad (4)$$

Using (4), it is easy to receive expressions for a remaining component electrical and magnetic field in plasma.

THE FEATURES OF THE ELECTROMAGNETIC FIELD DISTRIBUTION IN MAGNETIZED PLASMA

For example let's analyze the excitation of HF fields by surface charge with m=2. It is known that the solution in dielectric represents the superposition of TM-waves

($E_{zm}=\sum\limits_s A^{\pm}J_m\left(j_{ms}\dfrac{r}{a}\right)\exp(\pm k_{\|\mathrm{ms}}z)\exp(im\varphi)$, $B_z=0$)

and TE-waves

($B_{zm}=\sum\limits_p B^{\pm}J_m\left(j'_{mp}\dfrac{r}{a}\right)\exp(\pm k'_{\|\mathrm{mp}}z)\exp(im\varphi)$, $E_z=0$).

Here j_{ms} is the s-th root of a cylindrical functions of order m, j'_{mp} is p-th root of the derivative of cylindrical functions of order m,

$k_{\|ms}=\left(j_{ms}^2/a^2-\omega^2\varepsilon_d/c^2\right)^{1/2}$, $k'_{\|ms}=\left(j_{ms}'^2/a^2-\omega^2\varepsilon_d/c^2\right)^{1/2}$.

In the case of the non-magnetized plasma the solution have the same structure but in expression of $k_{\|}$ instead $\varepsilon_p=1-\omega_{pe}^2/\omega^2$ it is necessary to use ε_d. Let suppose that the surface charge on the antenna has such radial dependence $\sim J_2(j_{2,5}\,r/a)$.

Thus in case of non-magnetized plasma the HF field of TM-mode both in dielectric and plasma has the same radial distribution. The TE-mode is not excited in this case.

The external magnetic field completely changes the situation. In order to find the HF field in plasma it is necessary to fulfill the boundary conditions on interface of dielectric (II)-plasma (III): $\varepsilon_dE_{zII}=\varepsilon_3E_{zIII}$, $E_{\varphi II}=E_{\varphi III}$ and $B_{zII}=B_{zIII}$.

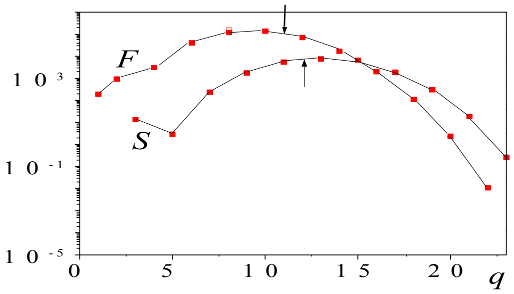

Fig.3. The amplitudes of the spatial harmonics (n.u.) in plasma with $n_e = 2.10^9 cm^{-3}$; surface charge $s = 5$. The harmonics of the curve F have $N^2_{\|q} > 0$, ones of the curve S correspond to $N^2_{\|q} < 0$. The arrows are marked position of the root with $j_{2,5}$

It results in the infinite system of linear equations concerning amplitudes C_q. We do not present its here because of its cumbersome. The amplitudes C_q were determined by numerical methods. Because the values of $j_{Fq} = N_{Fq} / a'$, and $j_{Sq} = N_{Sq} / a'$ are not equal $j_{2,5}$ determined the HF field radial structure in dielectric, the spectrum of harmonics (fig. 3) is excited in plasma. For these harmonics is $B_z \neq 0$. It results in appearance of the TE-mode in dielectric due to continuity of the B_z-component on plasma-dielectric interface. Also, there is the essential modification of the TM-mode field. As one can see from fig. 4 the field of this mode increase in center of the chamber and is decrease on its periphery.

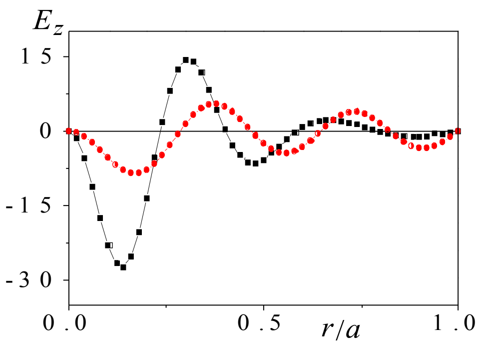

Fig. 4. The radial structure of the HF field in dielectric (n.u.) (♦) is the case of magnetized plasma, (•) is the case of non-magnetized plasma

These effects are stipulated by interaction of HF field with magnetized plasma. Let's analyze distribution of a HF of fields in plasma volume. As one can see from fig. 5,6 the HF field concentrated mainly in the central part of plasma volume. Thus the field smoothly decreases from the plasma-dielectric interface in the contrary to the case of non-magnetized plasma. Such behavior HF field along an axis z is stipulated by excitation of considerable number of harmonics with $N^2_{\|q} < 0$ that dependent from z proportionally $\cos[N_{\|q}(l - z)]$.

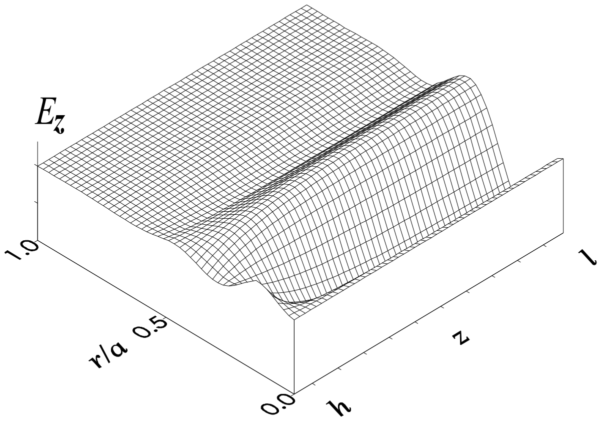

Fig.5. The distribution components E_z in plasma volume at $n_e = 2.10^9 cm^{-3}$

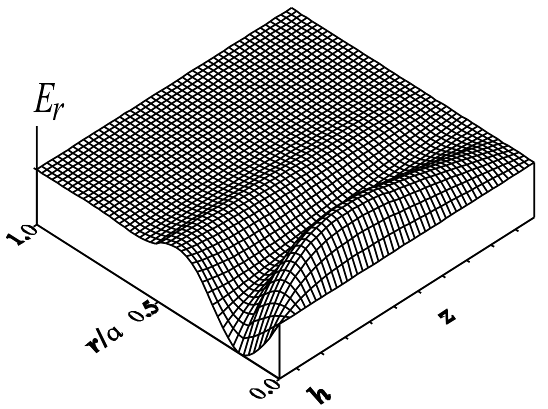

Fig.6. The distribution components E_r in plasma volume at $n_e = 2.10^9 cm^{-3}$

CONCLUSION

The HF field pattern in the PR-1 device in operational mode with an external magnetic field was studied. Considering the excitation of HF field by one azimuth and radial harmonics of a surface charge with frequency 13 MHz as the example, it was shown, that the presence of a magnetic field changes the HF field pattern both in dielectric, and in plasma. When the external magnetic field is turned off, the HF fields of the antenna is strongly screened by a surface charge on boundary dielectric - plasma and sharply decrease in plasma along axis of the device. The presence of a magnetic field results in more uniform distribution of fields along *Z*-axis and focusing them in center of plasma. Also, absolute value of of electric field considerably increases. The obtained qualitative conclusions can be generalized on the case of superposition of azimuth and radial harmonics at calculations of the actual antenna. So, the presence of an external magnetic field will allow to proceed to operational modes of the device with greater plasma density.

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РОЗПОДІЛ ВЧ ПОЛІВ В ПЛАЗМІ УСТАНОВКИ ПР-1 В МАГНІТНОМУ ПОЛІ

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Установка ПР-1 являє собою широкоапертурне джерело однорідної плазми, яке сконструйоване для обробки примірників великого діаметру, таких як елементи конструкції ВЧ антен та складові частини камери термоядерних установок. В роботі досліджено розподіл електромагнітних полів в камері установки, що працює в режимі з зовнішнім магнітним полем. Доведено, що в цьому режимі ВЧ поля краще проникають в плазму, ніж в режимі без магнітного поля. Тому в режимі з зовнішнім магнітним полем можливо створювати потік плазми з більшою густиною.

РАСПРЕДЕЛЕНИЕ ВЧ ПОЛЕЙ В ПЛАЗМЕ УСТАНОВКИ ПР-1 В МАГНИТНОМ ПОЛЕ

Д.Л. Греков, Н.А. Азаренков, А.А. Бизюков, В.П. Олефир

Установка ПР-1 предназначена для плазменной обработки образцов большого диаметра, таких как элементы конструкции ВЧ антенн и элементы камеры установок для магнитного удержания плазмы. В работе проведено изучение распределения ВЧ полей в объеме установки в режиме с внешним магнитным полем. Показано, что в этом случае ВЧ поля лучше проникают в плазму, чем без магнитного поля. Это позволит создавать плазменные потоки большей плотности.