

NUMERICAL MODELLING OF THE RF PLASMA PRODUCTION IN URAGAN-2M STELLARATOR WITH CRANKSHAFT ANTENNA

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The qualitative technique of the analysis of the efficiency of the RF plasma production is presented in which the solution of boundary problem for Maxwell’s equations is only necessary. The analysis of the character of the plasma production process with the crankshaft antenna in Uragan-2M stellarator is carried out. The discussion of the calculations results is presented.

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INTRODUCTION

Plasma production in the ion-cyclotron (IC) range of frequencies is the major method for plasma generation in Uragan-2M stellarator that starts to operate next year in the Kharkov Institute of Physics and Technology.

The features of plasma production in IC range of frequencies in toroidal magnetic devices are studied, and the stages of the plasma production process with increase of the plasma density are identified in Ref. [1].

In the paper [2] the crankshaft antenna is proposed, and it is has been shown its efficiency in the experiments on the radio-frequency (RF) plasma production on Uragan-3M small-size torsatron [3].

In the present work the results of study of plasma production in Uragan-2M stellarator with the crankshaft antenna obtained numerically are presented.

DESCRIPTION OF THE MODEL OF PLASMA PRODUCTION

The model of plasma production includes system of the balance equations and the boundary problem for the Maxwell equations. The system of the balance equations of particles and energy reads:

$$\begin{aligned} \frac{3}{2} \frac{\partial (n_e T_e)}{\partial t} &= P_{RFe} - \frac{3}{4} \varepsilon_H \langle \sigma_{e\nu} \rangle n_e n_a - \varepsilon_H \langle \sigma_{i\nu} \rangle n_e n_a \\ &+ \nabla \cdot \chi \nabla n_e T_e, \\ \frac{dn_e}{dt} &= \langle \sigma_{i\nu} \rangle n_e n_a + \nabla \cdot D \nabla n_e, \\ \int n_e dV + n_a V_V &= n V_V = const, \end{aligned} \quad (1)$$

where n_e is the plasma density, n_a is the neutral atoms density, T_e is the electron temperature, P_{RFe} is the RF power density, $\varepsilon_H = 13.6\text{eV}$ is the ionization threshold for hydrogen atom, $\langle \sigma_{e\nu} \rangle$ and $\langle \sigma_{i\nu} \rangle$ are the excitation and ionization rates, χ is the heat transport coefficient, D is the diffusion coefficient, V_V is the vacuum chamber volume.

To make the system of the equations (1) closed it is necessary to determine the single external parameter in it,

P_{RFe} . This parameter can be found from the solution of the boundary problem for the Maxwell’s equations:

$$\nabla \times \nabla \times \vec{E} - \frac{\omega^2}{c^2} \hat{\varepsilon}(r) \vec{E} = i\omega \mu_0 \vec{j}, \quad (2)$$

where E is the electric field, $\hat{\varepsilon}(r)$ is the dielectric tensor, j_{ext} is the external RF currents.

The system (1) describes the following physical processes during the plasma production. The electrons are heated by the RF field owing to collisional and Landau wave damping. The characteristic value of temperature is lower than the ionization threshold $T_e < \varepsilon_H$. In such conditions the ionization is made mainly by the “tail” of the electron distribution function. At low plasma density $n_e \ll n_a$ the system of the balance equations has a self-similar solution-

$$T_e = T_{er}(r), \quad n_e(r, t) = \exp(\nu t) n_{er}(r), \quad n_a = const,$$

and

$$P_{RF} = \exp(\nu t) P_{RF}(r). \quad (3)$$

From the self-similar solution follows that

$$S = \frac{P_{RF}}{n_e|_{r=0}} = f(r). \quad (4)$$

Such self-similar solution describes the mostly efficient plasma production. The degree of satisfying of the criterion (4) is used as an estimate of the plasma production performance.

The quantity (4) is analysed in the series of the calculations for the RF heating of plasma with the same density profile and increasing density values. Such a procedure allows one to avoid the long and labour-consuming solving the self-consistent problem (1, 2).

The crankshaft antenna (see Fig. 1) has three strap elements. The currents in the side straps are equal and phased. The current in the twisted central strap is double and directed opposite to the currents in the side straps.

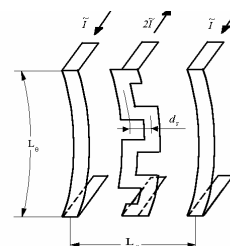


Fig. 1. Crankshaft antenna layout

RESULTS OF CALCULATIONS

The Maxwell's equations are solved using the 1D computer code that is based on the uniform finite elements method [4]. The parameters of calculations for Uragan-2M stellarator are chosen the following: the major radius of the torus is $R=1.5 \times 10^2$ cm, the radius of the plasma column is $r=20$ cm, the radius of the metallic wall is $a=30$ cm, the toroidal magnetic field is $B=5 \times 10^3$ G, the radial coordinate of the antenna strap $l_r=20$ cm, the electron temperature is $T_e=8$ eV. In the numerical experiments certain parameters are varied in the following range: the frequency of heating $\omega = 3 \times 10^7 \dots 4 \times 10^7$ s⁻¹, the amplitude of crankshaft twisting of the central conductor in the toroidal direction $\vartheta_a=0 \dots 0.04$, the distance between the side straps of the antenna $l_z=30 \dots 50$ cm. The quantity S is analyzed in the range of the plasma densities $n_{e0}=10^8 \dots 10^{13}$ cm⁻³, where $n_{e0} = n_e|_{r=0}$.

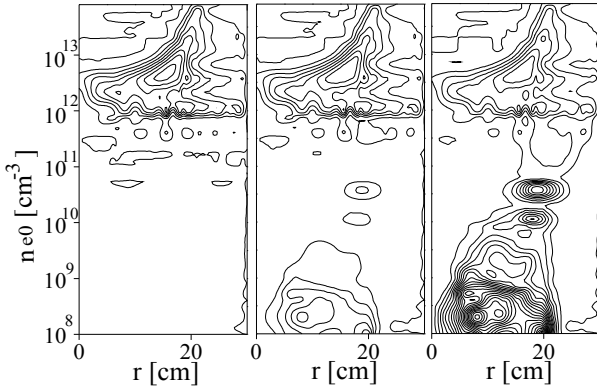


Fig. 2. Contours S as a function of plasma density at the centre of the plasma column n_{e0} and radial coordinate r for different values of amplitude of crankshaft twisting of the central conductor, $\vartheta_a=0$ (left figure), $\vartheta_a=0.02$ (central figure), $\vartheta_a=0.04$ (right figure)

In Fig. 2 the quantity S is shown for different crankshaft twisting of the central strap. In the left figure this parameter equals zero. The power deposition is small at low plasma densities. The power deposition appears at $n_{e0} > 3 \times 10^{12}$ cm⁻³ and reaches its optimum at $n_{e0} \sim 1 \times 10^{13}$ cm⁻³. The maximum of the power deposition is at $r=5$ cm in this case. At higher values of plasma density parameter S decreases and its distribution worsens.

With the introduction of the crankshaft twisting the power deposition increases at low plasma densities. At higher values of plasma density the power deposition shifts to the plasma edge and for high densities it is located in the vicinity of the antenna. At high plasma densities the power deposition into the centre of the plasma column remains the same as at $\vartheta_a=0$.

The calculations with varying ϑ_a have shown that it is not possible to achieve constancy of the quantity S with increase of the plasma density. The noticeable problem appears at the plasma densities $n_{e0} \sim 1 \times 10^{11}$ cm⁻³

at which the RF power does not reach the plasma core for reasonable values of ϑ_a .

The variation of the distance between the side straps does not influence on the low density plasma production (see Fig. 3). With the increase of this distance, the plasma density at which the power deposition is optimum decreases.

The variation of the heating frequency (see Fig. 4) gives the similar result: The optimum plasma density decreases with frequency.

If the parabolic density profile is changed to the hollow one, character of plasma production is altered (see Fig. 5). The radical change of the power deposition indicates the sensitivity of this method of plasma production to the radial distribution of plasma density. In the case of hollow plasma density profile the power deposition is more central at the plasma densities $n_{e0} \sim 1 \times 10^{11}$ cm⁻³. At higher densities then $n_{e0} > 1 \times 10^{12}$ cm⁻³ it worsens.

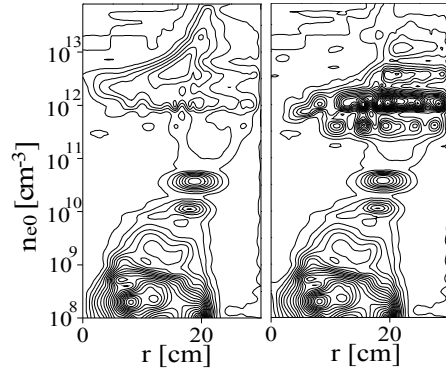


Fig. 3. The same as in Fig.2 for different values of distance between side straps, $l_z=30$ cm (left figure), $l_z=50$ cm (right figure)

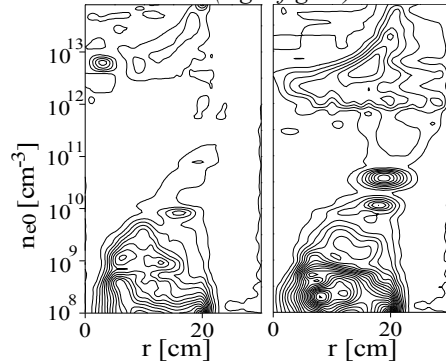


Fig. 4. The same as in Fig.2 for different values of frequency of heating, $\omega = 3 \times 10^7$ s⁻¹ (left figure), $\omega = 4 \times 10^7$ s⁻¹ (right figure)

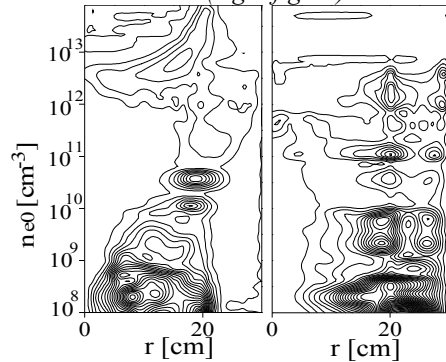


Fig. 5. The same as in Fig.2 for parabolic density profile (left figure) and for hollow density profile (right figure)

The results of the numerical experiments may be explained in the following way. At small values of the plasma density only the slow wave (SW) can propagate. The antenna without the crankshaft twisting cannot excite it, but even a small crankshaft twisting results in the efficient SW excitation. With increase of the plasma density the SW is strongly damped propagating to the centre of the plasma column. At $n_{e0} \sim 1 \times 10^{13} \text{ cm}^{-3}$ it is absorbed nearby the antenna.

The Alfvén resonances come to play at the plasma densities $n_{e0} \sim 1 \times 10^{12} \text{ cm}^{-3}$. Three-half-turn part of the antenna excites the Alfvén resonances efficiently. The overlapping between the direct SW generation and the Alfvén resonances excitation does not occur. There is the range of plasma densities $n_{e0} \sim 10^{11} \dots 10^{12} \text{ cm}^{-3}$ where the power deposition is minimal. In part, this can be improved by increasing of the frequency value, and also the power deposition is better for hollow density profile. If the frequency is higher the maximum plasma density which can be produced with crankshaft antenna will be lower.

CONCLUSIONS

Aiming to describe the RF plasma production in the Uragan-2M stellarator with the crankshaft antenna, the power deposition to the plasma with varying densities is analyzed numerically. At high plasma densities $n_{e0} \sim 10^{12} \dots 10^{13} \text{ cm}^{-3}$ and at low plasma densities $n_{e0} \sim 10^8 \dots 10^{10} \text{ cm}^{-3}$ the power deposition is acceptable for efficient plasma production. At high plasma densities there is some power deposition out of plasma column. At intermediate

densities, the RF field does not deliver the energy to the plasma centre. The situation improves if plasma has a hollow radial profile.

The calculations show that the reasonable choice for antenna parameters is the following: amplitude of crankshaft twisting of the central conductor in toroidal direction $\vartheta_a = 0.04$, the distance between the side straps of the antenna $l_z = 30 \text{ cm}$ number of the periods of the crankshaft twisting $n_c = 4$, the frequency of heating $\omega = 4 \times 10^7 \text{ s}^{-1}$. The estimate show that such an antenna is the able to produce plasma with the density $n_{e0} = 2 \times 10^{12} \text{ cm}^{-3}$ with the RF power $P = 600 \text{ kW}$.

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ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ВЫСОКОЧАСТОТНОГО СОЗДАНИЯ ПЛАЗМЫ В СТЕЛЛАТОРЕ УРАГАН-2М С ПОМОЩЬЮ АНТЕННЫ КОЛЕНВАЛЬНОГО ТИПА

В.Е. Моисеенко, Ю.С. Стадник, Е.Д. Волков, О.М. Швец

Представлена качественная методика анализа эффективности создания плазмы высокочастотными полями, в рамках которой необходимо только лишь решение уравнений Максвелла. Проведен анализ характера процесса создания плазмы в установке Ураган-2М с помощью антенны типа коленвал. Приведено обсуждение результатов расчетов.

ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ ВИСОКОЧАСТОТНОГО СТВОРЕННЯ ПЛАЗМИ У СТЕЛЛАТОРІ УРАГАН-2М ЗА ДОПОМОГОЮ АНТЕНИ КОЛЕНВАЛЬНОГО ТИПУ

В.Є. Моїсеєнко, Ю.С. Стаднік, Є.Д. Волков, О.М. Швець

Представлено якісну методику аналізу ефективності створення плазми високочастотними полями, в межах якої необхідне лише розв'язання рівнянь Максвелла. Проведено аналіз характеру процесу створення плазми в установці Ураган-2М за допомогою антени типу коленвал. Приведено обговорення результатів розрахунків.