SELF-CONSISTENT MODEL OF THE RF PLASMA PRODUCTION IN STELLARATOR

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Self-consistent model of the RF plasma production in stellarator that includes system of the balance equations and the boundary problem for the Maxwell's equations is developed. The first numerical calculations of RF plasma production in the Uragan-2M stellarator are presented.

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INTRODUCTION

Plasma production in the ICRF band (Ion Cyclotron Range of Frequencies) is a possible way to build up dense target plasma in a stellarator (see [1]). The self-consistent model developed here simulates plasma production with arbitrary ICRF antennas and includes system of the particle and energy balance equations for the electrons and neutrals and the boundary problem for the Maxwell's equations. Solution of the Maxwell's equations allows determining a local value of the electron RF heating power, which influences on the ionization rate and, in this way, on the evolution of plasma density.

At small values of the plasma density, the slow wave (SW) is responsible for plasma production. With increase of the plasma density the SW is strongly damped propagating to the centre of the plasma column and is absorbed in the antenna vicinity. At high values of the plasma density, the Alfvén resonances come to play in the plasma production. The electrons are heated by the RF field owing to collisional and Landau wave damping.

NUMERICAL MODEL

The model of the radio-frequency (RF) plasma production includes the system of the balance equations and the boundary problem for the Maxwell's equations. It is assumed that the gas is atomic hydrogen. The system of the balance equations of particles and energy reads:

$$\frac{3}{2}\frac{\partial(k_B n_e T_e)}{\partial t} = P_{RFe} - \frac{3}{4}k_B\varepsilon_H\langle\sigma_e \mathrm{v}\rangle n_e n_a - \\ -(C_a+1)\frac{k_B n_e T_e}{\tau_E} - k_B\varepsilon_H\langle\sigma_i \mathrm{v}\rangle n_e n_a + \nabla\cdot\chi\nabla(n_e T_e), \quad (1)$$

$$\frac{dn_e}{dt} = \langle\sigma_i \mathrm{v}\rangle n_e n_a - \frac{n_e}{\tau_E} + \nabla\cdot D\nabla n_e ,$$

$$\int n_e dV + n_a V_V = n_0 V_V = const ,$$

where n_e is the plasma density, n_a is the neutral gas density, T_e is the electron temperature, P_{RFe} is the RF power density, which is coupled to the electrons, k_B is the Boltzman's constant, $\varepsilon_H = 13.6\,eV$ is the ionization potential threshold for the hydrogen atom, χ is the heat transport coefficient, D is the diffusion coefficient, τ_E is the particle confinement time, V_V is the vacuum chamber volume, $\langle\sigma_e \mathrm{v}\rangle$, $\langle\sigma_i \mathrm{v}\rangle$ are the excitation and ionization rates and $C_a = e\Phi_a / T_e \approx 3.5$ is the ratio of the ambipolar potential energy to the electron temperature. Dependence of the excitation and ionization rates of atoms by the electron impact on electron temperature is approximated by formulas:

$$\langle\sigma_e \mathrm{v}\rangle = 2k_s \exp\left(-\frac{3}{4}\frac{\varepsilon_H}{T_e}\right),$$
$$\langle\sigma_i \mathrm{v}\rangle = 3.8k_s \frac{T_e}{\varepsilon_H}\exp\left(-\frac{\varepsilon_H}{T_e}\right). \quad (2)$$

Balance of the electron energy includes the RF heating, energy losses for the excitation and ionization of atoms and losses caused by the heat transport. The balance of the charged particles includes accounts for the ionization and diffusion losses of particles. The last equation in the system (1) reflects the global balance of the particles. It is assumed, that the neutral gas is uniformly distributed in the vacuum chamber volume, including the plasma column.

The RF field can produce plasma inside the confinement volume and outside it as well. The losses of the charged particles in the outside region have a convection character: the particles escape to the wall along the lines of force of the magnetic field. Such losses of particles outside the confinement volume are described in τ -approximation. The τ -approximation is also used inside the plasma column to describe energy exchange with ions. Out of the confinement region the particle confinement time is given by the following formula:

$$\tau_n = \frac{RL}{2\mathrm{v}_s}, \quad (3)$$

where R is the local mirror ratio, L is the connection length of the magnetic field line, v_s is the ion sound velocity in plasma.

The problem is solved in cylindrical geometry. The plasma is assumed to be azimuthally symmetrical and uniformly distributed along plasma column. The length of plasma cylinder is $L = 2\pi R$ and the ends are assumed to be identical.

The account of the diffusion and the thermal conductivity effects require application of the conditions of regularity at the axis of the cylinder:

$$\left.\frac{\partial n_e}{\partial r}\right|_{r=0} = 0\,,\quad \left.\frac{\partial (n_e T_e)}{\partial r}\right|_{r=0} = 0\,, \tag{4}$$

and boundary conditions

$$n_e\big|_{r=a} = 0\,,\ n_e T_e\big|_{r=a} = 0 \tag{5}$$

at the chamber wall.

To make the system of the equations (1) closed, it is necessary to determine the single external quantity in it, P_{RFe} (RF power density). This quantity can be found from the solution of the boundary problem for the Maxwell's equations:

$$\nabla\times\nabla\times\mathbf{E} - \frac{\omega^2}{c^2}\hat{\varepsilon}(r)\cdot\mathbf{E} = i\omega\mu_0\mathbf{j}_{ext}\,, \tag{6}$$

where $\mathbf{E}$ is the electric field, $\mathbf{j}_{ext}$ is the external RF currents. The dielectric tensor reads:

$$\hat{\varepsilon}(r,t) = \begin{pmatrix} \varepsilon_\perp & ig & 0 \\ -ig & \varepsilon_\perp & 0 \\ 0 & 0 & \varepsilon_{//} \end{pmatrix},\ \text{where}\ \varepsilon_\perp = \frac{\varepsilon_{++} + \varepsilon_{--}}{2}\,,$$

$$\varepsilon_{//} = 1 + \frac{2\omega_{P\alpha}^2}{k_z(\omega + i\nu_\alpha)} z_\alpha\left[1 + i\sqrt{\pi} z_\alpha W(z_\alpha)\right],\ g = \frac{\varepsilon_{++} - \varepsilon_{--}}{2}\,,$$

$$\varepsilon_{++} = 1 + \frac{\omega_{P\alpha i}^2}{\omega_{c\alpha}(\omega_{c\alpha} - \omega - i\nu_\alpha)}\,,$$

$$\varepsilon_{--} = 1 + \frac{\omega_{P\alpha}^2}{\omega_{c\alpha}(\omega_{c\alpha} + \omega + i\nu_\alpha)}\,.$$

The Maxwell's equations are solved at each time moment for current plasma density and temperature distributions. The Maxwell's equations solution allows determining the value of local RF heating power of the electron plasma component which influences on the ionization rate and, in this way, on the increase of plasma density. The RF power density in cylindrical system of coordinates reads:

$$P_{RF} = \frac{\omega\varepsilon_0}{2}\mathrm{Im}\big(|E_r|^2\varepsilon_\perp + |E_\varphi|^2\varepsilon_\perp + |E_z|^2\varepsilon_{//} + 2E_r E_\varphi^* \mathrm{Im}g\big). \tag{7}$$

The Crank-Nicholson method is used for the solving of system of the balance equations (1). The Maxwell's equations (6) are solved in the 1D geometry using the Fourier series in the azimuthal and the axial coordinates. For the discretization in the radial coordinate, the uniform finite elements method is employed that uses a special set of weight (test) and basis (shape) functions [2].

EXAMPLE OF CALCULATIONS

The following parameters of calculations for the Uragan-2M stellarator are chosen: the major radius of the torus is $R = 1.7\times10^2\,\mathrm{cm}$, the radius of the plasma column is $r = 22\,\mathrm{cm}$, the radius of the metallic wall is $a = 34\,\mathrm{cm}$, the radial coordinate of the antenna is $r_{ant} = 23\,\mathrm{cm}$, the toroidal magnetic field is $B = 5\,\mathrm{kG}$. The frame-type antenna (Fig. 1) with the azimuthal angle $\varphi_a = 1$ and the toroidal angle $\vartheta_a = 0.08$ was used in the calculations. The current in the antenna is assumed not varying along the conductors.

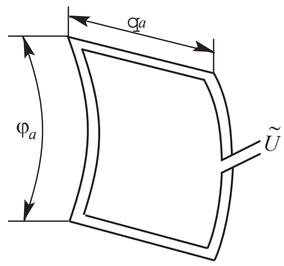

Fig. 1. Frame antenna layout

The first results of calculations of RF plasma production in the Uragan-2M stellarator are presented. Figs. 2, 3 display profiles of plasma density, electron temperature and power deposition at the time moment $t = 0.45\cdot10^{-2}$ s. Figs. 4-6 display the time evolution of electron temperature, plasma density and density of neutral gas.

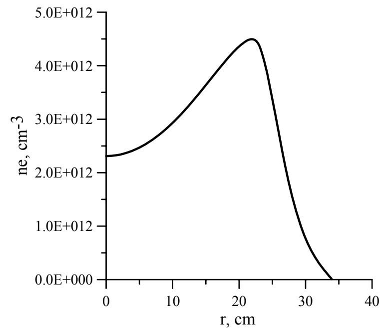

Fig. 2. Profile of plasma density in $t = 0.45\cdot10^{-2}$ s

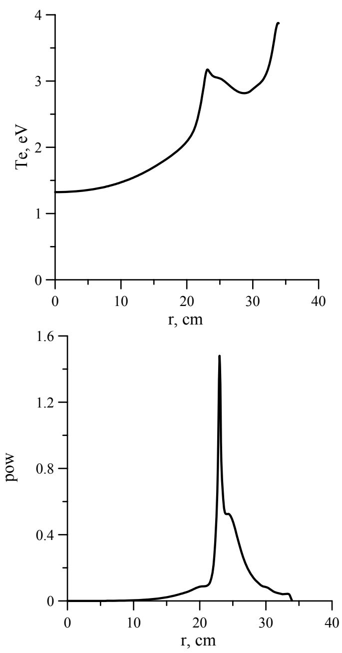

Fig. 3. Profile of electron temperature (upper chart) and power deposition profile (lower chart) in time moment $t = 0.45\cdot10^{-2}$ s

A characteristic feature of the calculations is higher plasma temperature outside the confinement volume (Fig. 3). Since the heating power-per-particle is higher at lower plasma densities (Fig. 2) the electron temperature increases at the edge of the plasma column (Fig. 3) where the particle losses are faster.

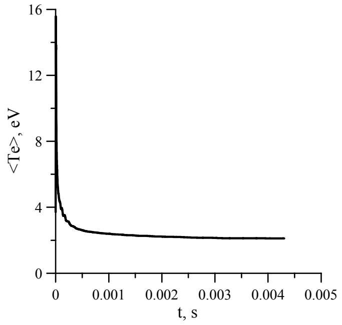

Fig.4. Time evolution of average electron temperature

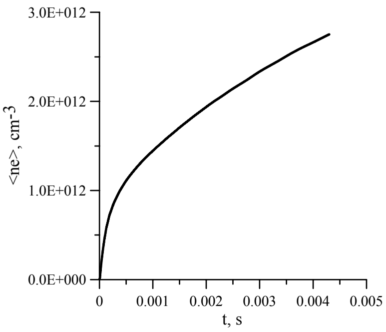

Fig. 5. Time evolution of average plasma density

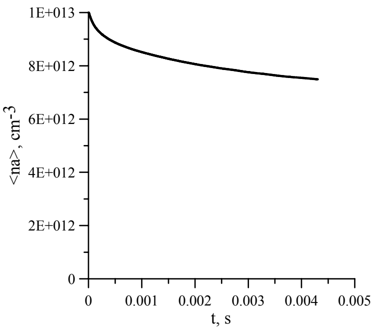

Fig. 6. Time evolution of average neutral atoms density

At the initial stage of the plasma production, sharp peaks in temperature are observed (Fig. 4). These peaks are associated with the sharp increase of the antenna loading resistance. It occurs when the wave global resonance conditions in a plasma column is met. At the initial stage of plasma production a slow wave damping is small, and the peaks of the global resonances are more narrow and high.

In the chosen regime, the plasma density rise saturates and the plasma production process has a tendency to stagnate because the power is insufficient to complete a burnout of the neutral atoms (Figs. 5, 6).

CONCLUSIONS

For the self-consistent description of ICRF plasma production in stellarators, the numerical model including a system of the balance equations for particles and energy and the boundary problem for the Maxwell's equations is developed.

The Crank-Nicholson method is used for solving the system of the balance equations. The Maxwell's equations are solved using the Fourier series in the azimuthal and the longitudinal coordinates. Fortran90 computer code is developed.

Using the self-consistent model for the ICRF plasma production in stellarators the first numerical calculations for the Uragan-2M stellarator are carried out.

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САМОСОГЛАСОВАННАЯ МОДЕЛЬ ВЧ-СОЗДАНИЯ ПЛАЗМЫ В СТЕЛЛАРАТОРЕ

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Разработана самосогласованная модель ВЧ-создания плазмы в стеллараторе, включающая систему уравнений баланса и краевую задачу для уравнений Максвелла. Представлены первые результаты численных экспериментов по ВЧ-созданию плазмы в стеллараторе Ураган-2М с помощью разработанной модели.

САМОУЗГОДЖЕНА МОДЕЛЬ ВЧ-СТВОРЕННЯ ПЛАЗМИ У СТЕЛЛАРАТОРІ

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Розроблено самоузгоджену модель ВЧ-створення плазми в стеллараторі, що складається з системи рівнянь балансу та крайової задачі для рівнянь Максвелла. Представлено перші результати числових експериментів з ВЧ-створення плазми в стеллараторі Ураган-2М за допомогою розробленої моделі.