NUMERICAL MODELLING OF PLASMA PRODUCTION WITH RADIO-FREQUENCY HEATING USING FOUR-STRAP π-PHASED ANTENNA

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Results of calculations of radio-frequency (RF) plasma production in the ion-cyclotron range of frequencies (ICRF) in the Uragan-2M stellarator using four-strap π-phased antenna are presented. The analysis carried out with usage of a self-consistent model that simulates plasma production with ICRF antennas.

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INTRODUCTION

Plasma production in ICRF is most efficient if the frequency is lower than the ion cyclotron frequency. The features of plasma production in ICRF in toroidal magnetic devices are studied, and the stages of the plasma production process with an increase of the plasma density are identified in Refs. [1, 2]. The problem of RF plasma generation can be reformulated as the problem of RF heating of a low-density low-temperature plasma. The plasma density grows from the value determined by the natural level of ionizing radiation to the value corresponding to the full ionization of the neutral gas. Since the range of plasma densities is fairly wide, it is possible to distinguish three stages of RF plasma generation that differ in both the distribution of the electromagnetic field and the character of the ionization process. In the first (wave-less) stage (breakdown of the neutral gas), the plasma density is very low and only slightly affects the structure of the electromagnetic field. The second stage is preliminary gas ionization; in this stage, waves can already propagate in the plasma, but the plasma density is still lower than the neutral gas density. The third stage is the stage of neutral gas burnout; in this stage, the plasma density becomes comparable with the neutral gas density.

In Uragan-2M stellarator plasma is regularly produced by the frame antenna. However, the frame antenna cannot generate plasma with high enough density. Numerical calculations have shown the effectiveness of the frame antenna for low density plasma production [3, 4]. Starting from the plasma density $n_{e0}\sim10^{12}\,cm^{-3}$ the power deposition becomes periphery located and this cannot be avoided by changing of antenna sizes and other parameters. For this reason plasma density can be obtained with such an antenna is not high that is confirmed by first experiments in Uragan-2M device [4]. The resulting plasma density is of order $n_{e0}\sim2\cdot10^{12}\,cm^{-3}$. However, there is a need to operate with plasma of the density of at least several times higher. Further increase of plasma density to $n_{e0}\sim10^{13}\,cm^{-3}$ could be provided by RF heating with another antenna system.

The four-strap antenna is oriented to the Alfvén heating in the short wavelength regime [5]. Therefore, the antenna is π -phased. Of course, the $k_{||}$ range of this antenna is not optimal for plasma production and it does not allow such an antenna to produce plasma. To operate successfully, the four-strap antenna needs initial plasma with noticeable density.

In this paper we investigate whether four-strap antenna is able to increase the plasma density in Uragan-2M stellarator. In our scenario, the frame antenna produces plasma with partial ionization with the density, which it is able to produce. The four-strap antenna increases plasma density and provide full neutral gas ionization.

The self-consistent model of the RF plasma production in stellarators [2] is applied to this problem.

NUMERICAL MODEL

The model of the 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 stellarator plasma column is modeled as a straight plasma cylinder with identical electric fields at its ends (periodicity condition). The plasma is assumed to be axisymmetric, radially non-uniform and uniformly distributed along the plasma column.

The system of the balance equations of particles and energy reads:

$$
\begin{aligned}
&\frac{3}{2}\frac{\partial (k_B n_e T_e)}{\partial t} = P_{RF} - \frac{3}{4}k_B\varepsilon_H\langle\sigma_e \mathrm{v}\rangle n_e n_a - k_B\varepsilon_H\langle\sigma_i \mathrm{v}\rangle n_e n_a - \\
&-\frac{3}{2}k_B\langle\sigma_{ei}\mathrm{v}\rangle n_e^2 (T_e - T_i) - (C_a+1)\frac{k_B n_e T_i}{\tau_n} - \\
&-\frac{k_B}{r}\frac{\partial}{\partial r}r\left(q_e + \Gamma_e T_e - \chi n_e\frac{\partial T_e}{\partial r}\right) - e\Gamma_e E_r, \\
&\frac{dn_e}{dt} = \langle\sigma_i \mathrm{v}\rangle n_e n_a - \frac{n_e}{\tau_n} - \frac{1}{r}\frac{\partial}{\partial r}r\Gamma_e, \qquad (1)\\
&\int n_e dV + n_a V_V = n_0 V_V = const,
\end{aligned}
$$

where n_e is the plasma density, n_a is the neutral gas density, n_0 is the initial neutral gas density, T_e is the electron temperature, P_{RFe} is the RF power density of electron heating, k_B is the Boltzmann constant, ε_H=13.6 eV is the ionization energy threshold of a hydrogen atom, τ_n is the particle confinement time, the coefficient 3/4 is the ratio of the excitation energy to the

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ionization energy, V_V is the vacuum chamber volume, $\langle\sigma_e v\rangle$ is the rate of electron-impact excitation of an atom, $\langle\sigma_i v\rangle$ is the rate of electron-impact ionization of an atom, $\langle\sigma_{ei} v\rangle$ is the rate of electron-ion energy exchange via Coulomb collisions, and $C_a = e\Phi_a/T_e \approx 3.5$ is the ratio of the electron energy in the ambipolar potential to the electron thermal energy. Only electrons with energies higher than the potential energy $e\Phi_a$ leave the plasma. Accordingly, energy losses per electron increase by a factor of C_a in average.

The neoclassical particle flux Γ_e and energy flux q_e are

$$\Gamma_e = -n_e D_1 \left\{ \left(\frac{1}{n_e}\frac{\partial n_e}{\partial r} + \frac{eE_r}{k_B T_e} \right) + \left(\frac{D_2}{D_1} - \frac{3}{2} \right) \frac{1}{T_e}\frac{\partial T_e}{\partial r} \right\},$$

$$q_e = -n_e T_e D_2 \left\{ \left(\frac{1}{n_e}\frac{\partial n_e}{\partial r} + \frac{eE_r}{k_B T_e} \right) + \left(\frac{D_3}{D_2} - \frac{3}{2} \right) \frac{1}{T_e}\frac{\partial T_e}{\partial r} \right\}.$$

In this formulas

$$D_n = \frac{2}{\sqrt{\pi}} \int_0^\infty dK_e e^{-K_e} K_e^{l-1/2} D_{11} \quad (l = 1...4),$$

$$K_e = \frac{m_e v_e^2}{2k_B T_e}, \quad D_{11} = D_{11}\left(r, \frac{\nu_e}{v_e}, \frac{E_r}{v_e B_0} \right),$$

where D_{11} is the monoenergetic diffusion coefficient, m_e is the electron mass, v_e is the electron velocity, ν_e is the collision frequency, and E_r is the radial component of the electric field.

The RF field produces plasma both inside and outside the confinement region. Charged particle losses outside the confinement region are caused not only by diffusion, but also convection, because the plasma particles escape onto the chamber wall along the magnetic field lines, as is the case in open traps [6]. The model takes into account this process in the τ-approximation with $\tau_n = \Pi L/2v_s$. Here, Π is the mirror ratio, which was assumed to be unity in our simulations, L is the length of a magnetic field line, and v_s is the ion-acoustic velocity. This formula describes plasma expansion along the magnetic field with the speed of sound. Expression is applicable only to plasma located outside the confinement region. Inside the confinement region, the characteristic time of convective losses is infinite.

The problem of particle and energy transfer requires setting the following regularity conditions at the cylinder axis

$$\left.\frac{\partial n_e}{\partial r}\right|_{r=0} = 0, \quad \left.\frac{\partial (n_e T_e)}{\partial r}\right|_{r=0} = 0. \tag{2}$$

The boundary conditions at the chamber wall,

$$n_e|_{r=a} = 0, \quad n_e T_e|_{r=a} = 0 \tag{3}$$

correspond to a zero plasma density and plasma energy at the wall.

To make the system of the equations (1) closed, it is necessary to determine RF power density,

$$P_{RF} = \frac{\omega}{2} \sum_{m,n} \mathrm{Im}\left(\mathbf{E}^*_{mn} \cdot \mathbf{D}_{mn} \right), \tag{4}$$

where m and n are the azimuthal and toroidal mode numbers, respectively. This quantity can be found from the solution of the boundary problem for the Maxwell's equations

$$\nabla \times \nabla \times \mathbf{E} - \frac{\omega^2}{c^2} \varepsilon\,\mathbf{E} = i\omega\mu_0 \mathbf{j}_{ext}, \tag{5}$$

where **E** is the temporal Fourier harmonics of the electric field and $\mathbf{j}_{ext}$ is the density of the external RF current. The plasma dielectric tensor is a function of the plasma density and electron temperature,

$$\varepsilon(r,t) = \begin{pmatrix} \varepsilon_\perp & ig & 0 \\ -ig & \varepsilon_\perp & 0 \\ 0 & 0 & \varepsilon_{//} \end{pmatrix}.$$

All components of the plasma dielectric tensor, except for $\varepsilon_\parallel$, are taken in the cold plasma approximation. For the ion and electron temperatures of T~2…20 eV, which are typical of the initial stage of plasma production, the particle gyroradius is much smaller than the wavelength and the finite-Larmor-radius corrections to the tensor can be ignored. At the same time, the value of $k_\parallel v_{Te}$ can be comparable with the frequency ω (in particular, when generating plasma in small stellarators), which indicates that it is necessary to take into account electron Landau damping and use the expression for the tensor component $\varepsilon_\parallel$ in the hot plasma approximation.

In cylindrical geometry the Fourier series could be used

$$\mathbf{E} = \sum_{m,n} E_{mn}(\mathbf{r}) e^{im\varphi} e^{ikz} e^{-i\omega t}. \tag{6}$$

The Maxwell's equations are solved at each time moment for current plasma density and temperature distributions.

EXAMPLES OF CALCULATIONS

The following parameters of calculations for the Uragan-2M stellarator are chosen: the major radius of the torus is $R = 1.7\cdot 10^2$ cm; the radius of the plasma column is $r_{pl} = 22$ cm; the radius of the metallic wall is $a = 34$ cm; the toroidal magnetic field is B=5 kG. The radial coordinate of the front surface of four-strap antenna (Fig. 1) is $r_{ant} = 28$ cm; the distance between antenna strap elements in z-direction is $l_z = 20$ cm. Antenna is simulated by external RF currents $\mathbf{j}_{ext}$ which obey to the condition $\nabla\cdot\mathbf{j}_{ext} = 0$. The explicit expressions for the Fourier harmonics of the antenna currents are substituted to the Maxwell's equations.

For this antenna the leading value of parallel wave-number is $k_\parallel = 0.16$ cm^{-1}. The most efficient Landau damping occurs when $k_\parallel v_{Te} \sim \omega$ this corresponds to the electron temperature of 35 eV. The lower $k_\parallel$ modes of antenna spectrum need higher electron temperature to be damped efficiently.

Simulation results are presented in Figs.2-7. The parameters of numerical calculations were as follows: the initial electron temperature was $T_e = 2$ eV; the ion temperature was taken to be independent of the radius and time, $T_i = 3$ eV; the frequency of heating was $\omega = 4\cdot 10^7$ s^{-1}.

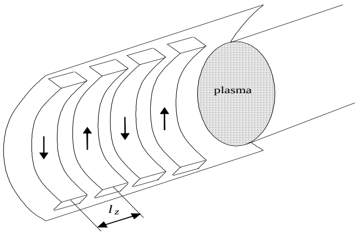

Fig. 1. Four-strap antenna layout

The first numerical experiments have shown that the four-strap antenna cannot create plasma if initial plasma density is lower than $n_{e0}=5\cdot10^{11}$ cm^{-3}, where $n_{e0}=n_e|_{r=0}$ [7]. In current numerical experiments initial plasma density was n_{e0}~10^{12} cm^{-3}; the antenna current for the matched load was I_0=800 A. The initial density of neutral atoms was in the range $n_0=1\cdot10^{12}\ldots4\cdot10^{12}$ cm^{-3}.

Figures 2-4 display the time evolution of average plasma density, average electron temperature and average density of neutral atoms. Figures 5-7 display the profiles of plasma density, electron temperature and deposited power at the time moment t=1.5 ms.

Just after the start, the plasma density begins to increase (see Fig. 2). The first two stages of plasma production (the wave-less and preionization stages) pass very rapidly.

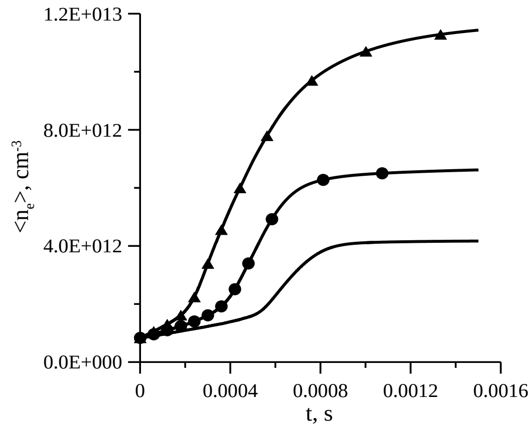

Fig. 2. Time evolution of the average plasma density for different values of the initial density of the neutral atoms $n_0=1\cdot10^{12}$ cm^{-3} (unmarked curve), $n_0=2\cdot10^{12}$ cm^{-3} (circles), $n_0=4\cdot10^{12}$ cm^{-3} (triangles)

At the initial stage of the plasma production the average electron temperature is low. This is due to low coupling of antenna to plasma. Further, the antenna loading improves and plasma production is accelerated. The electron temperature increases (see Figs. 2, 3).

At the end of the ionization process the density of the neutral gas decreases to a value determined by particle recycling (see Fig. 4).

The generated plasma density profile has a maximum in the center of the plasma column (see Fig. 5). The electron temperature and the power deposition are low at the center of the plasma column (see Figs. 6, 7).

The calculations have shown that optimal value of the initial neutral gas density is atoms $n_0=2\cdot10^{12}$ cm^{-3}. The power deposition occurs within the plasma volume in this case (see Fig. 7). As in the case of the frame-type antenna [2], by using the four-strap antenna, the peripheral

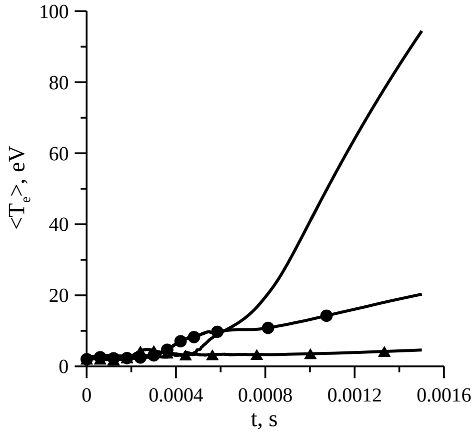

Fig. 3.Time evolution of the average electron temperature for different values of the initial density of the neutral atoms $n_0=1\cdot10^{12}$ cm^{-3} (unmarked curve), $n_0=2\cdot10^{12}$ cm^{-3} (circles), $n_0=4\cdot10^{12}$ cm^{-3} (triangles)

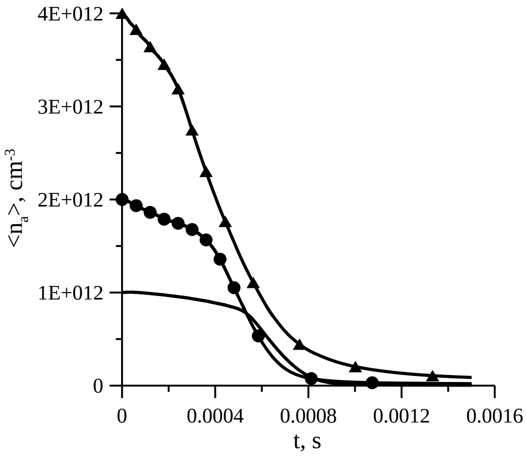

Fig. 4. Time evolution of the average density of neutral atoms for different values of the initial density of the neutral atoms $n_0=1\cdot10^{12}$ cm^{-3} (unmarked curve), $n_0=2\cdot10^{12}$ cm^{-3} (circles), $n_0=4\cdot10^{12}$ cm^{-3} (triangles)

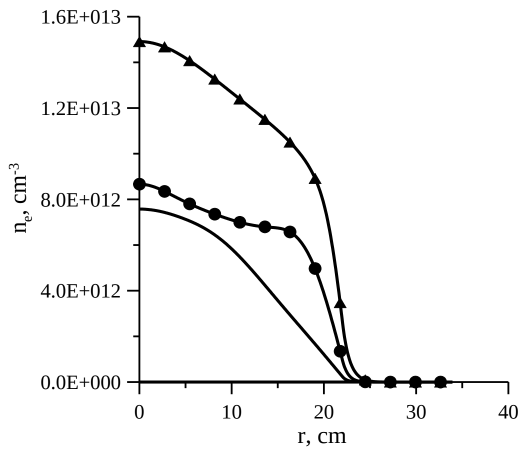

Fig. 5. Plasma density profile at t=1.5 ms for different values of the initial density of the neutral atoms $n_0=1\cdot10^{12}$ cm^{-3} (unmarked curve), $n_0=2\cdot10^{12}$ cm^{-3} (circles), $n_0=4\cdot10^{12}$ cm^{-3} (triangles)

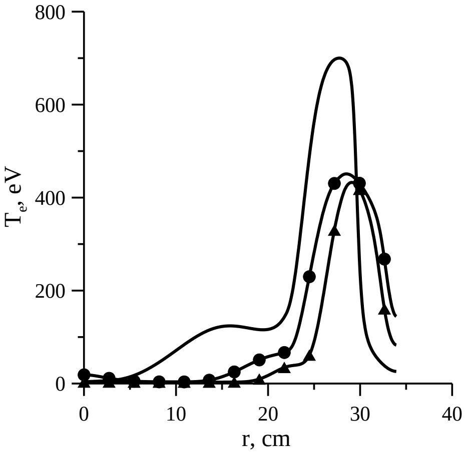

Fig. 6. Electron temperature profile at t=1.5 ms for different values of the initial density of the neutral atoms $n_0=1\cdot10^{12}$ cm^{-3} (unmarked curve), $n_0=2\cdot10^{12}$ cm^{-3} (circles), $n_0=4\cdot10^{12}$ cm^{-3} (triangles)

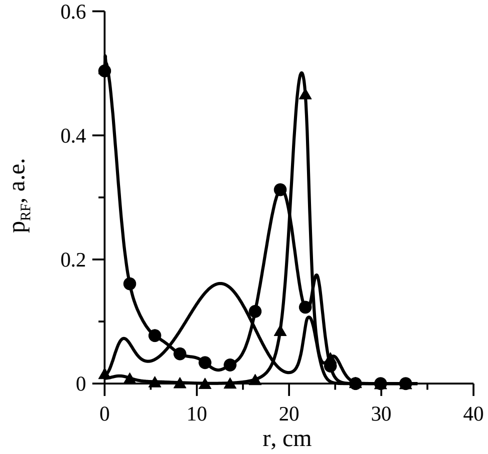

Fig. 7. Power deposition profile at t=1.5 ms for different values of the initial density of the neutral atoms $n_0=1\cdot10^{12}$ cm^{-3} (unmarked curve), $n_0=2\cdot10^{12}$ cm^{-3} (circles), $n_0=4\cdot10^{12}$ cm^{-3} (triangles)

plasma is also heated to high temperatures (see Fig. 6). It can be explained by the Landau damping of the slow wave at the plasma periphery. Unlike the frame-type antenna slow wave is excited by the conversion of the fast wave field in the Alfvén resonance layer. When the neutral gas density increases, the resulting plasma density is somewhat higher (see Fig. 5), the power deposition profile is shifted toward the antenna (see Fig. 7), whereby the electron temperature within the plasma column decreases (see Fig.6).

DISCUSSION

The numerical calculations for Uragan-2M stellarator indicated that using the four-strap antenna plasma density can be increased by an order of magnitude during the pulse. For chosen discharge parameters, the optimal value of the initial neutral gas density is $n_0=2\cdot10^{12}$ cm^{-3}.

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САМОСОГЛАСОВАННОЕ МОДЕЛИРОВАНИЕ ВОЗРАСТАНИЯ ПЛОТНОСТИ ПЛАЗМЫ С ВЫСОКОЧАСТОТНЫМ НАГРЕВОМ

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Представлены результаты расчетов по ВЧ-созданию плазмы в ионно-циклотронном (ИЦ) диапазоне частот в стеллараторе Ураган-2М с использованием четырехполувитковой π-фазированной антенны. Теоретический анализ проводился с помощью самосогласованной модели, которая моделирует создание плазмы с использованием ИЦ-антенн.

САМОУЗГОДЖЕНЕ МОДЕЛЮВАННЯ ЗРОСТАННЯ ГУСТИНИ ПЛАЗМИ ВИСОКОЧАСТОТНИМ НАГРІВОМ

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Представлено результати розрахунків з ВЧ-створення плазми в іонно-циклотронному (ІЦ) діапазоні частот у стелараторі Ураган-2М з використанням чотирьохнапіввиткової π-фазованої антени. Теоретичний аналіз проводився за допомогою самоузгодженої моделі, що моделює створення плазми з використанням ІЦ-антен.