SELF-CONSISTENT MODELLING OF PLASMA DENSITY INCREASE WITH RADIO-FREQUENCY HEATING

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The self-consistent model of the radio-frequency (RF) plasma production in stellarators is described in this work. With this model of plasma production, one can perform calculations for different antenna systems. The self-consistent model includes the system of the particle and energy balance equations and the boundary problem for the Maxwell’s equations. The numerical calculations of RF plasma production with four-strap antenna in the Uragan-2M stellarator are presented.

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INTRODUCTION

The physical base of plasma production is the electron impact ionization of a neutral gas. For electrons, the maximum of the cross-section takes place for the energies several times exceeding the threshold ε (ε = 13.6 eV for hydrogen atom). One can perform rough estimates for plasma production time

\[ \tau \sim \frac{1}{n_e a} \frac{\varepsilon}{m_e} \]

(here V is the plasma volume). For the magnetic fusion parameters the plasma production time appears very short and the power is much higher that is usual for plasma auxiliary heating. Because the plasma production time is not a parameter of primary importance, it can be extended up to the hot plasma confinement time. This allows one to decrease the RF power level. In this regime, the majority of the electron population have the energy below the ionization threshold. The ionization is performed by the tail of the electron distribution function.

In stellarator type machines, besides the electron-cyclotron method, the plasma production in the ion-cyclotron range of frequencies is practiced (see [1]). The self-consistent model of the RF plasma production [2] in stellarators is applied for this problem. With this model one can perform calculations for different antenna systems. The self-consistent model includes the system of the particle and energy balance equations and the boundary problem for the Maxwell’s equations. Solution of the Maxwell’s equations determines 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.

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 system of the balance equations of particles and energy reads:

\[
\frac{3}{2} \frac{\partial (k_e n_e T_e)}{\partial t} = P_{ee} - \frac{3}{4} k_e n_e \langle \sigma_r \rangle n_e^n - k_e n_e \langle \sigma_i \rangle n_e^n - \frac{3}{2} k_e \langle \sigma_e \rangle n_e^n T_e - (C_e + 1) \frac{k_e n_e T_e}{\tau_e} + \nabla \cdot \chi(n, T_e)
\]

\[
\frac{dn_e}{dt} = \langle \sigma_e \rangle n_e n_i - \frac{n_e}{\tau_e} + \nabla \cdot D n_e
\]

where \( n_e \) is the plasma density, \( n_i \) is the neutral gas density, \( T_e \) is the electron temperature, \( P_{ee} \) is the RF power density that is coupled to the electrons, \( k_e \) is the Boltzmann’s constant, \( \varepsilon = 13.6 \text{ eV} \) is the ionization energy threshold for the hydrogen atom, \( \chi \) is the heat transport coefficient, \( D \) is the diffusion coefficient, \( \tau_e \) is the particle confinement time, \( V_r \) is the vacuum chamber volume, \( \langle \sigma_e \rangle \) and \( \langle \sigma_i \rangle \) are the excitation and ionization rates, \( \chi(n, T_e) \) is the energy exchange rate with ions via Coulomb collisions, and \( C_e = eE_{\text{ext}} / T_e \approx 3.5 \) is the ratio of the ambipolar potential energy to the electron temperature.

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

\[
\nabla \times \nabla \times \mathbf{E} - \frac{\omega^2}{c^2} \hat{\mathbf{E}}(r) - i \omega \mu_0 j_{\text{ext}}
\]

(2)

where \( \mathbf{E} \) is the electric field, \( j_{\text{ext}} \) is the external RF currents. The dielectric tensor reads:

\[
\hat{\chi}(r, t) = \begin{pmatrix}
\varepsilon_\perp & i \kappa & 0 \\
-i \kappa & \varepsilon_\perp & 0 \\
0 & 0 & \varepsilon_\parallel
\end{pmatrix}
\]

In cylindrical geometry the Fourier series could be used:

\[
\mathbf{E} = \sum_{n \omega} \mathbf{E}(r)e^{in\phi} e^{i\omega t} e^{-\omega t}
\]

The Maxwell’s equations are solved at each time moment for current plasma density and temperature distributions.
EXAMPLE OF CALCULATIONS

The following parameters of calculations for the Uragan-2M stellarator are chosen: the major radius of the torus is \( R = 1.7 \cdot 10^7 \text{cm} \), the radius of the plasma column is \( r = 22 \text{cm} \), the radius of the metallic wall is \( a = 34 \text{cm} \), the toroidal magnetic field is \( B = 5 \text{kG} \), the frequency of heating \( f = 4 \cdot 10^7 \text{s}^{-1} \). The radial coordinate of the front surface of four-strap antenna (Fig. 1) is \( l_r = 28 \text{cm} \), the distance between antenna strap elements in \( z \)-direction is \( l_z = 20 \text{cm} \). Antenna is simulated by external RF currents \( \mathbf{j}_{\text{ext}} \) which obeys to the condition \( \nabla \cdot \mathbf{j}_{\text{ext}} = 0 \). The explicit expressions for the Fourier harmonics of the antenna currents are substituted to the Maxwell’s equations.

The numerical experiments have shown that the four strap antenna cannot create plasma if initial plasma density is lower than \( n_{\text{p0}} = 5 \cdot 10^{12} \text{cm}^{-3} \) (here \( n_{\text{p0}} = n|_{t=0} \)). For higher initial densities the fully ionized plasma is built-up.

The results of calculations of RF plasma production in the Uragan-2M stellarator with the four-strap antenna are presented in figures 2 and 3 which display the profiles of plasma density, electron temperature and deposited power at the time moment \( t = 0.5 \text{ms} \). Figures 4-6 display the time evolution of electron temperature, plasma density and density of neutral gas.

The power deposition and the electron temperature (see Fig. 3) are low at the center of the plasma column. At the center of the plasma column the plasma density has a hollow profile (see Fig. 2). Since the power deposition profile has a maximum near the plasma edge, the ionization rate is higher there and plasma density growth at the center is owing to plasma diffusion from the periphery to the center.

RF power is also deposited out of the plasma confinement volume. Therefore low density plasma is sustained there.
Starting from $t = 0.4$ ms the antenna loading improves and plasma production is accelerated. The electron temperature increases (Fig. 6).

At the end of the ionization process the density of the neutral gas (Fig. 7) decreases to a value determined by particle recycling.

**CONCLUSIONS**

Using the self-consistent model for the ICRF plasma production the numerical calculations for the Uragan-2M stellarator with the four-strap antenna are carried out.

The numerical calculations have shown that the four-strap antenna is able to produce plasma. But there is density threshold $n_e = 5 \cdot 10^{11}$ cm$^{-3}$ below which the plasma production process stagnate. If the initial density is higher than the threshold, the neutral gas burns out fully and the centrally peaked plasma density profile is formed.

**REFERENCES**


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