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THEORETICAL ANALYSIS OF RF PLASMA PRODUCTION IN URAGAN-2M TORSATRON

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Introduction

Plasma production in ICRF (Ion Cyclotron Range of Frequencies) is most efficient if the frequency is lower then the ion cyclotron. 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 Ref. [1]. The frame antenna and the crankshaft antenna (Fig. 1) are proposed, and they are has been shown their efficiency in the experiments on the radio-frequency (RF) plasma production at Uragan-3M small-size torsatron [1, 2].

In the present report the results of the numerical study on plasma production in Uragan-2M torsatron which recently has started the operation at Kharkiv with the frame and the crankshaft antennas are presented.

Numerical Model

The Maxwell's equations

$$\nabla \times \nabla \times \vec{E} - \frac{\omega^2}{c^2} \hat{\varepsilon}(r) \cdot \vec{E} = i\omega\mu_0 \vec{j} , \qquad (1)$$

are solved in the cylindrical radially non-uniform plasma. Here $\vec{E}$ is the electric field, $\hat{\varepsilon}(r)$ is the dielectric tensor, $\vec{j}_{\text{ext}}$ is the external RF current. The dielectric tensor accounts for the collisional and the Landau damping. Then the quantity

$$S = P_{RFe} / n_e \qquad (2)$$

which is the RF power delivered per electron is calculated. Here P_{RFe} is the RF power density and n_e is the density of the plasma electron component. The local ionization rate is proportional to S. The radial distribution of S is analysed in the series of the calculations for the RF heating of plasma with the same plasma density profile and increasing plasma density values.

Numerical Results

The Maxwell's equations are solved using the 1D computer code that uses Fourier transform in the azimuthal and the longitudinal coordinates. For the discretization in radial coordinate,

For the frame antenna the power deposition is bulk at low densities $n_{e0} < 10^{10}\,\mathrm{cm}^{-3}$. With the plasma density increase the power deposition shifts to the plasma periphery. This shifts starts earlier for higher RF frequencies. For the crankshaft antenna the pictures are similar, but with some central power deposition at high densities. This power deposition could be associated with Alfvén resonance excitations. It migrates to lower plasma densities for higher frequencies. This series of calculations prompts that the plasma density profile which is formed self consistently could be hollow, especially in the density range $10^{10}\,\mathrm{cm}^{-3} < n_{e0} < 10^{12}\,\mathrm{cm}^{-3}$.

If the density profile is hollow, the character of plasma production is altered (see Figs. 5 and 6). The visible change of the power deposition indicates the sensitivity of plasma production to the radial distribution of plasma density. The power deposition is more central at the plasma densities $n_{e0} \sim 10^{10}\,\mathrm{cm}^{-3}$. At higher densities $n_{e0} > 10^{11}\,\mathrm{cm}^{-3}$ it is better than for parabolic profile, but still not sufficiently central.

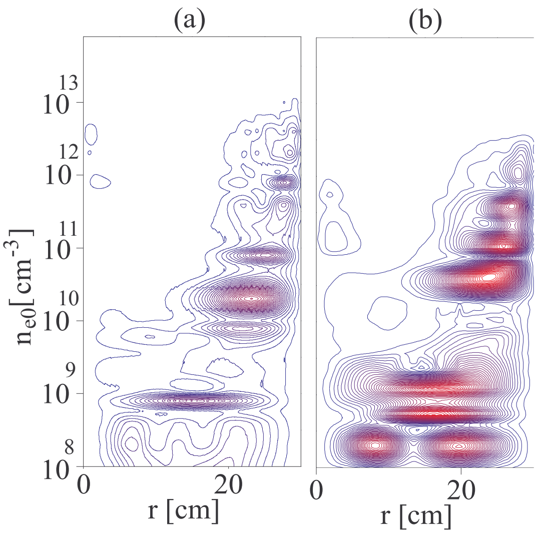

Fig. 5 Contours of S as a function of radial coordinate r and plasma density at the centre of the plasma column n_{e0} for different values of RF frequency, $\omega = 3\times10^{7}\,\mathrm{s}^{-1}$ (a), $\omega = 4\times10^{7}\,\mathrm{s}^{-1}$ (b) for the hollow density profile for the frame antenna.

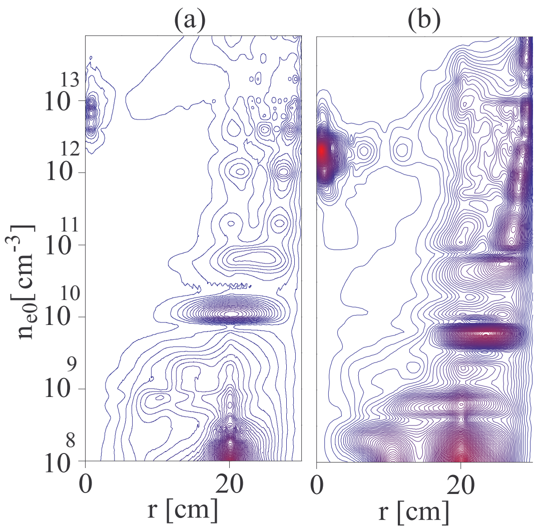

Fig. 6 Contours of S as a function of radial coordinate r and plasma density at the centre of the plasma column n_{e0} for different values of RF frequency, $\omega = 3\times10^{7}\,\mathrm{s}^{-1}$ (a), $\omega = 4\times10^{7}\,\mathrm{s}^{-1}$ (b) for the hollow density profile for the crankshaft antenna.

Note here that at low plasma densities only the slow wave (SW) can propagate. On increase of the plasma density the damping of the SW increases and at $n_{e0} > 10^{12}\,\mathrm{cm}^{-3}$ it is absorbed nearby the antenna. The Alfvén resonances can deliver the RF power into plasma core. They come to play at high plasma densities $n_{e0} > 10^{12}\,\mathrm{cm}^{-3}$. They are visible at the charts for the crankshaft antenna, but not visible at the frame antenna charts.

Discussion

The numerical calculations have shown the effectiveness of the frame antenna for low density plasma production. Starting from the plasma density $n_{e0} \sim 10^{10}\,\mathrm{cm}^{-3}$ the power deposition becomes periphery located and this can not be avoided by changing of antenna sizes and other parameters. For this reason plasma density that can be obtained with such an antenna is low what is clearly confirmed by the first experiments at Uragan-2M [4]. This antenna could be used if, after the frame antenna RF pulse, further increase of plasma density to $n_{e0} \sim 1-3\times10^{13}\,\mathrm{cm}^{-3}$ could be provided by the RF heating with core power deposition that is accompanied with a gas puff or a pellet injection.

The crankshaft antenna provides acceptable power deposition at low and high plasma densities. The power deposition has a minimum at the plasma densities $10^{10}\,\mathrm{cm}^{-3} < n_{e0} < 10^{11}\,\mathrm{cm}^{-3}$ that makes this stage of plasma production critical. The crankshaft antenna could be used for dense plasma production $n_{e0} \sim 10^{13}\,\mathrm{cm}^{-3}$. But the power threshold for this antenna which is determined by the critical stage is high. The estimate show that such an antenna is able to produce plasma with the density $n_{e0} \sim 4\times10^{12}\,\mathrm{cm}^{-3}$ with the RF power $P = 600\mathrm{kW}$.

References

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