MODELLING OF ELECTROMAGNETIC FIELD IN BOX OF UNSHIELDED 'ICRF' ANTENNA

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1. Introduction

Plasma heating by radiation in the ion-cyclotron range of frequencies (ICRF) is one of the most promising methods of auxiliary heating. The radiation is launched into a plasma by an antenna composed of a central conductor surrounded laterally by protecting walls, that form an antenna box. Conventionally an array of metallic blades, a Faraday shield (FS), is placed over the front of the antenna box. However along with positive effects an FS has adverse ones which become more pronounced with rise in radiated power. Reconsideration of the concept of an FS and successful experiments with the unshielded ICRF antenna on the tokamak TEXTOR [1-3] have provoked the interest in plasma behavior and field distribution inside the antenna box. Modelling of the plasma interaction with a potential component of radio-frequency (RF) field in the box of antenna without FS have shown the formation of the oscillating charge layer which acts as a virtual plate of a capacitor, while the other plate is the central conductor. This led to almost complete shielding of the electrostatic component inside the box [4, 5]. Consequently, a strong variation of electromagnetic field polarization along the depth of the box is expected. To study the electromagnetic field structure in the antenna box the development of the previous electrostatic model is proposed.

2. Model

Electromagnetic radiation from the antenna box is caused by the (external) current in the central conductor (Fig. 1). Just inside the box the plasma strongly reacts to the RF field, and in turn modifies it. The peculiarity of this plasma response is associated with the relatively small connection length (= the width of the box), which makes possible considerable variations of electron and ion densities during RF period. Oscillations of the charge result from a balance of particles which get into the box moving across the toroidal magnetic fields $\mathbf{B}_0$ in the radial direction (x) and escape to the walls of the box in the toroidal direction (z) in the presence of RF field. The plasma and electromagnetic field in the box of unshielded antenna and in the front of it are self-consistently described by the following equations

$$\frac{\partial n_\alpha}{\partial t} + \frac{\partial}{\partial x}(n_\alpha V_{\alpha x}) + \frac{2}{L}[nV_z]_\alpha = 0, \tag{1}$$

$$m_\alpha n_\alpha \frac{\partial V_{\alpha x}}{\partial t} = q_\alpha n_\alpha (E_x + V_{\alpha y} B_0/c) - T_\alpha \frac{\partial n_\alpha}{\partial x} - \nu_{\alpha\perp} m_\alpha n_\alpha V_{\alpha x} + \eta_\alpha \frac{\partial^2 V_{\alpha x}}{\partial x^2}, \tag{2}$$

$$m_\alpha n_\alpha \frac{\partial V_{\alpha y}}{\partial t} = q_\alpha n_\alpha (E_y - V_{\alpha x} B_0/c) - \nu_{\alpha\perp} m_\alpha n_\alpha V_{\alpha y} + \eta_\alpha \frac{\partial^2 V_{\alpha y}}{\partial x^2}, \tag{3}$$

$$c \,\mathrm{rot}\, \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + 4\pi \sum_{\alpha=i,e} q_\alpha n_\alpha \mathbf{V}_{\alpha\perp}, \tag{4}$$

$$c \,\mathrm{rot}\, \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \tag{5}$$

$$\mathrm{div}\, \mathbf{E} = 4\pi \sum_{\alpha=i,e} q_\alpha n_\alpha, \tag{6}$$

where n_α and $\mathbf{V}_{\alpha\perp}$ – density and transverse velocity of the species; $q_\alpha = \pm e$ and m_α – charge and mass, T_α, $\nu_{\alpha\perp}$ and η_α – effective temperature, transverse collision frequency and viscosity, $\alpha = i, e$. We consider the RF field with the components $\mathbf{E}(x,y) = \{E_x, E_y, 0\}$ and $\mathbf{B}(x,y) = \{0, 0, B_z\}$. The quantities $n_\alpha, \mathbf{V}_{\alpha\perp}$, $\mathbf{E}$, $\mathbf{B}$ are averaged over the box width L, e.g.

$$\mathbf{E}(x,y) = \frac{1}{L} \int_{-L/2}^{L/2} \mathbf{E}(x,y,z)\, dz\,.$$

Alternatively, the field can be described in terms of the scalar and vector potentials φ and $\mathbf{A} = \{A_x, A_y, 0\}$, so that

$$E_x = -\frac{\partial \varphi}{\partial x} - \frac{1}{c}\frac{\partial A_x}{\partial t}, \qquad E_y = -\frac{\partial \varphi}{\partial y} - \frac{1}{c}\frac{\partial A_y}{\partial t}, \qquad B_z = \frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y}. \tag{7}$$

To close the system of these equations z-fluxes to the walls at the positions $z = \pm L/2$ in Eq.(1) are expressed in terms of averaged n_α and φ [4, 5]. Inside the box we have

$$[nV_z]_\alpha = n_\alpha \sqrt{\frac{T_\alpha}{m_\alpha}} \times \begin{cases} \exp\left(q_\alpha \varphi / T_\alpha\right), & q_\alpha \varphi \le 0, \\ 1, & q_\alpha \varphi > 0, \quad n_\alpha \le n_\beta, \quad \alpha = e, i\,, \\ 1 + (1 - n_\beta/n_\alpha)\, \sqrt{2 q_\alpha \varphi / T_\alpha}\,, & q_\alpha \varphi > 0, \quad n_\alpha > n_\beta, \quad \beta = i, e\,. \end{cases} \tag{8}$$

Outside the box for z-fluxes at $z = \pm L/2$ we take

$$[nV_z]_\alpha = n_\alpha \sqrt{\frac{T_\alpha}{m_\alpha}} \times \begin{cases} 1 - \exp\left(-q_\alpha \left(\varphi - \varphi_{fl}\right)/T_\alpha\right), & q_\alpha \varphi \ge q_\alpha \varphi_{fl}, \\ -1 + \exp\left(q_\alpha \left(\varphi - \varphi_{fl}\right)/T_\alpha\right), & q_\alpha \varphi < q_\alpha \varphi_{fl}, \end{cases} \quad \alpha = e, i\,, \tag{9}$$

where $\varphi_{fl} = \ln \sqrt{T_e m_i / T_i m_e}$ is a floating potential. (Fluxes (8), (9) differ from that in [4, 5] in an insignificant factor.)

The system of nonlinear model equations (1)–(9) is solved with the boundary conditions at $x = 3\,cm$:

$$n_i = n_e = 0, \quad \varphi = 472 (T_e/e) \sin(2\pi f \cdot t), \quad A_x = 0, \quad A_y = -132 (T_e/e) \cos(2\pi f \cdot t). \tag{10}$$

The boundary conditions for the field correspond to the external current in the central conductor $j_{cc} \sim \sin(\pi y / 2l) \cos(2\pi f \cdot t) \delta(x - 3)$ and are taken in the plane of simulation positioned at $y = l/2$, the middle of the central conductor poloidal extension. Global poloidal inhomogeneity of the field is not ignored. The particle densities and velocities, however, are supposed to be locally uniform in the poloidal direction since particle excursions during the RF period are two order less than l.

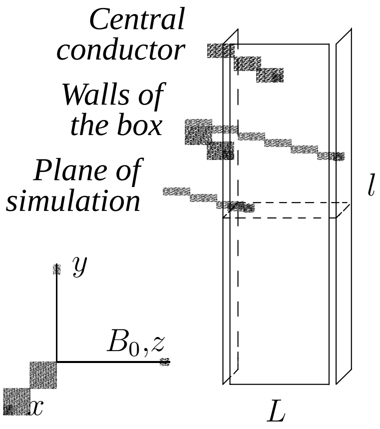

Figure 1. Antenna box. The plane of simulation at $y = l/2$ is indicated.

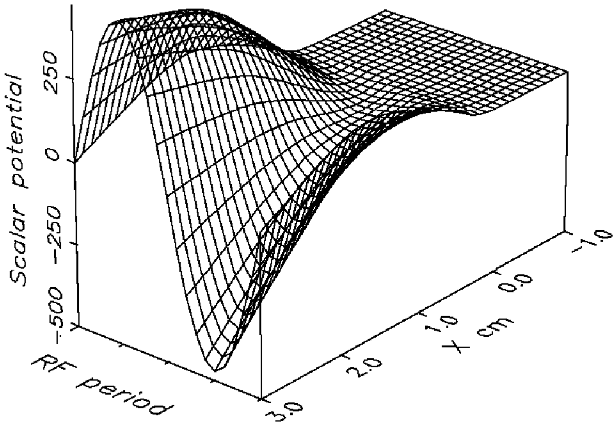

Figure 2. Variation of the dimensionless scalar potential $e\varphi/T_e$.

3. Scalar and vector potentials

Numerical solutions were obtained for plasma parameters that are typical for the TEXTOR tokamak $n_{i,e}\,(x = -3\,cm) = 2 \times 10^{12}\,cm^{-3},\ T_i = 60\,eV,\ T_e = 30\,eV,\ B_0 = 3\,T,\ m_i = 2m_p,\ l = 70\,cm,\ L = 26\,cm$ and $f = 3 \cdot 10^7\,Hz$. The radial distributions of the dimensionless potentials $e\varphi/T_e,\ eA_y/T_e$ and eA_x/T_e at the interval $-1\,cm \le x \le 3\,cm$ and their variations during the RF period are given in Figs. 2–4.

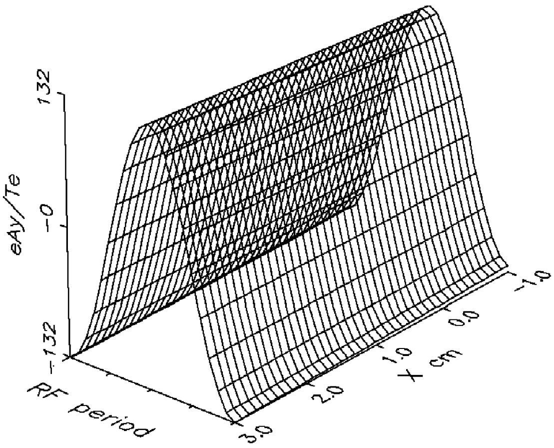

Figure 3. Variation of the dimensionless y-component of vector potential eA_y/T_e.

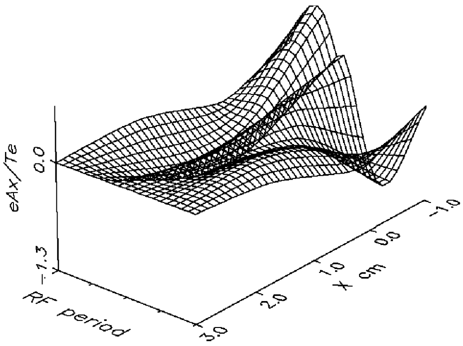

Figure 4. Variation of the dimensionless x-component of vector potential eA_x/T_e.

At the position of the central conductor, $x = 3\,cm$, the variations of the potentials is determined by the external sources. Fig. 2 shows a strong shielding of the scalar potential φ at the edge of the box, x=0. In contrast, the plasma in the box has relatively little effect on the poloidal component of vector potential A_y (Fig. 3). The increase of the radial component of vector potential A_x towards the plasma core is shown in Fig. 4; note the value of A_x at the edge of the box remains two order less then A_y. The difference in mass between ions and electrons and the nonlinearities in z-fluxes (8), (9) manifest themselves in nonsinusoidal forms of A_x and φ in vicinity of the box mouth, where the potentials are small. As it follows from Figs. 2-4 and Eq. (7) the radial component of electric field E_x, which prevail over E_y in vicinity of the central conductor, $x \approx 3\,cm$, strongly decreases in front of the box, at $x \approx -1\,cm$.

4. Discussion

Present simulation has supported the idea put forward in [1] that without FS plasma itself will filter out the electrostatic component. The results are also in agreement with the previous work [5], where formation of the layer of an oscillating charge inside the box was predicted, and thus was proposed the particular mechanism of the shielding of an electrostatic component. However the fine structure of the shielding charge is more irregular that it was found earlier, and this result along with the distribution of transverse particle fluxes will be reported elsewhere.

5. Conclusions

The self-consistent description of a plasma and electromagnetic field in the unshielded box of the ICRF antenna is proposed. The radial and temporal distributions of the scalar and vector potentials are calculated. Due to the small connection length there is a considerable variation of charge density in the box during the RF period, which causes the decrease of the scalar potential towards the plasma core. Whereas the currents in the box are not strong enough to modify the vector potential substantially. Together it results in the strong variation of the field polarization over a distance of 3-4 cm from the central conductor.

Acknowledgments

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