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Theoretical analysis of ion cyclotron range of frequency antenna array for HT-7U

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This paper considers the coupling analysis of phased antenna array designed to excite fast wave in the ion cyclotron range of frequency. The coupling of the antenna is calculated in slab geometry. The coupling code based on the variational principle gives the self-consistent current flowing in the antenna, this method has been extended so that it can be applied to a phased antenna array. As an example, this paper analyses the coupling prosperities of a 2×2 phased antenna array. It gives the optimum geometry of antenna array. The fields excited at plasma surface are found to more or less correspond to the antenna current phasing.

Keywords: ion cyclotron range of frequency, antenna array, variational method
PACC: 5240F, 5250, 5265

1. Introduction

The HT-7U superconducting tokamak is a part of national project in China on fusion research.[1] The radio frequency method of plasma heating will play an important role in the planned HT-7U tokamak experiments. In HT-7U, ion cyclotron range of frequencies (ICRF) heating is to be employed. It is therefore important to optimize the antenna design and its coupling to the plasma. Some papers have been devoted to this problem.[2,3]

Theilhaber and Jacquinot presented[4] a variational theory for obtaining the self-consistent current in the straps for an ICRF antenna without lateral structures and developed[5] a coupling code for an analysis of the trombone antenna in JET. SAIGUSA[6] extended Theilhaber and Jacquinot's coupling code for a toroidal trombone antenna array with solid septa. Reference [7] demonstrates high coupling performance of JT-60U ICRF antennas. In order to analyses the coupling prosperities of the fast wave antennas array, we have extended Theilhaber and Jacquinot's coupling code for the antenna array in the present paper. It is the aim of this paper to present a theoretical model of the ICRF antenna array. The theory developed here makes it possible to calculate the ICRF antenna array. It is used to do an accurate and well optimized design of the antenna. The principal numerical calculations performed for HT-7U parameter are given in Section 3.

The main theoretical results of this work are presented in Section 2, where the wave differential equation for the ICRF electromagnetic field and assumptions of the model are given. In Section 3 we investigate the dependence of the radiation impedance on antenna parameters and the corresponding field structures at plasma surface. Section 4 presents a summary from our investigation and discusses the implications for design of the antenna.

2. The three-dimensional and basic equation

2.1. Description of the model

The model of the ICRF antenna array is shown in Fig.1. The toroidal direction in tokamak is z coordinate, the poloidal direction is along y coordinate, and the radial direction is along x coordinate. The direction of the confining magnetic field line has an angle α with the antenna current. Each of the antenna array consists of a horizontal feeding strap and a vertical radiating strap. The wall is at $x = 0$, the current straps is at $x = b$, the screen is at $x = c$, the plasma

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edge is at $x = d$. The centre of connecting of the feeding strap is at $x = 0, y = \pm h, z = z_i$. The width of each current strap is $-w/2 < z < w/2$, and the short circuit at $x = 0, y = 0, z = z_i$. The electrostatic screen is modelled by a homogeneous anisotropic layer, with infinite conductivity parallel to the magnetic field and zero conductivity perpendicular to it. The screen is completely opaque to TM modes, and completely transparent to the TE modes, which carry the power into the plasma.

The plasma is taken as semi-infinite and has a linear density profile. We assume that the plasma is sufficiently absorbed to suppress cavity eigenmodes, so that no power is reflected back onto the antenna structures. We only consider the coupling to the fast wave.

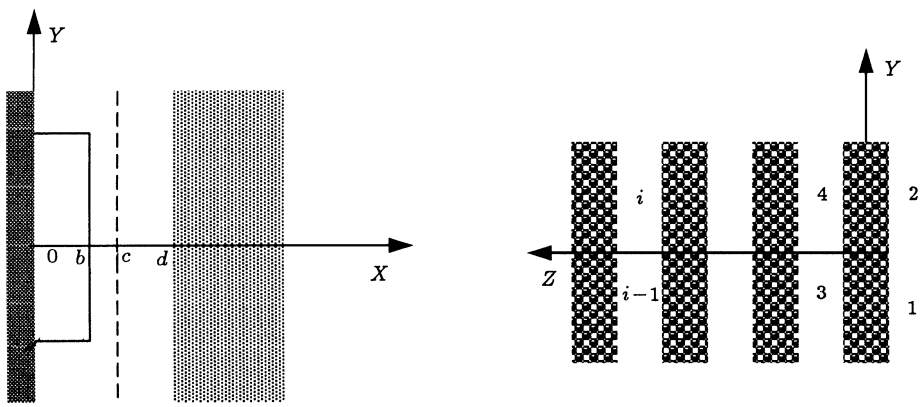


Fig.1. Geometry of the coupling model: (a) poloidal cross-sectional view, and (b)schematic view, of the toroidal antenna array.

2.2. Derivation of the wave equations

We recall here the expressions of the electromagnetic field in Ref [2].We normalize Maxwell's equations in the calculations by using the following replacements:

$$\bar{\boldsymbol{x}} = \frac{\omega}{c}\bar{\boldsymbol{x}}_{\mathrm{p}}, \quad \boldsymbol{E} = \boldsymbol{E}_{\mathrm{p}}, \tag{1}$$

$$\boldsymbol{H} = (u_0/\varepsilon_0)^{1/2}\boldsymbol{H}_{\mathrm{p}}, \quad \boldsymbol{J} = (1/\omega_0\varepsilon_0)\boldsymbol{J}_{\mathrm{p}}, \tag{2}$$

where the subscript "p" denotes the physical quantity.

We model the current on the central conductor of the antenna by the distribution

$$\boldsymbol{J} = J_y(y,z)\delta(x-b)\boldsymbol{e}_y + J_x(y,z)u(b-x)\boldsymbol{e}_x. \tag{3}$$

To calculate the antenna–plasma coupling and the antenna input impedance, the electromagnetic field must be solved. According to the Maxwell equations, subjecting to the standard boundary condition,[4] we can obtain the equations for the z components of the electric and magnetic field

$$\left(\frac{\mathrm{d}^2}{\mathrm{d}x^2} - \Gamma^2\right) E_z = n_z\left(\mathrm{i}n_y J_y - J_x\right)\delta\left(x-b\right), \tag{4}$$

$$\left(\frac{\mathrm{d}^2}{\mathrm{d}x^2} - \Gamma^2\right) H_z = -J_y\delta\left(x-b\right) + \mathrm{i}n_y J_x u\left(b-x\right), \tag{5}$$

where $\Gamma^2 = n_y^2 + n_z^2 - 1$, n_y and n_z are the poloidal and toroidal wavenumber.

Once the components E_z and H_z are solved, the other field components can be expressed easily in terms of these two components and the current density:

$$E_x = \frac{1}{1-n_z^2}\left[\mathrm{i}n_z\frac{\mathrm{d}E_z}{\mathrm{d}x} - n_y H_z\right] - \mathrm{i}\frac{J_x u\left(b-x\right)}{1-n_z^2}, \tag{6}$$

$$E_y = \frac{1}{1-n_z^2}\left[-n_y n_z E_z - \mathrm{i}\frac{\mathrm{d}H_z}{\mathrm{d}x}\right] - \mathrm{i}\frac{J_y\delta\left(x-b\right)}{1-n_z^2}, \tag{7}$$

$$H_x = \frac{1}{1-n_z^2}\left[\mathrm{i}n_z\frac{\mathrm{d}H_z}{\mathrm{d}x} + n_y E_z\right] + \mathrm{i}\frac{n_z J_y\delta\left(x-b\right)}{1-n_z^2}, \tag{8}$$

$$H_y = \frac{1}{1-n_z^2}\left[-n_y n_z H_z + \mathrm{i}\frac{\mathrm{d}E_z}{\mathrm{d}x}\right] - \mathrm{i}\frac{n_z J_x u\left(b-x\right)}{1-n_z^2}. \tag{9}$$

The function $Y_{\mathrm{p}}\left(n_y, n_z\right)$ is the spectral admittance in the space $x \geq d$, defined by

$$Y_{\mathrm{p}}\left(n_y, n_z\right) = H_z\left(x = d, n_y, n_z\right)/E_y\left(x = d, n_y, n_z\right), \tag{10}$$

where E_z and H_z are the fields in the plasma and are obtained by integrating the coupled fast-wave equations. It is summarized in Appendix B of Ref.[4].

2.3. The current profiles on the antenna

We assumed that the source at $y = \pm h$ is dis-

tributed along a thin band $z_i - w/2 < z < z_i + w/2$ at $x = 0$.The electric field generated by the power source can be written as

$$E_{\rm s}^i = \delta(x)\, Q_i(y,z)\, V_{\rm s}^i \boldsymbol{e}_x, \tag{11}$$

where $Q_i(y,z) = 1$ on the feeder strap and $Q_i(y,z) = 0$ elsewhere. $V_{\rm s}^i$ is the generated voltage and $\boldsymbol{e}_x$ is the unit vector in the x direction.

The condition of zero tangential electric field on the strap can be written as

$$E_{\rm s}^i + E_{\rm ind}^i = 0, \tag{12}$$

where $E_{\rm ind}^i$ is the electric field vector on the ith strap. It is induced by the current on the ith strap. It can be written in operator form,

$$E_{\rm ind}^i = \boldsymbol{L}^i \cdot \boldsymbol{j}^i. \tag{13}$$

We have

$$V_{\rm s}^i = Z_{\rm A}^i I_J^i = Z_{\rm A}^i \int j_x^i(x=0,y,z) Q_i(y,z)\,{\rm d}y{\rm d}z. \tag{14}$$

Equation (12) becomes an eigenvalue equation for the antenna impedance $Z_{\rm A}^i$. Once Eq.(12) is solved for all indexes i, it also gives the current profiles $j_x(x,y,z)$ and $j_y(x,y,z)$. In order to form a variational principle, we multiply Eq.(12) by an arbitrary $\boldsymbol{k}^i$ defined on the ith strap. According to Eqs.(11) and (13), we have

$$\int \boldsymbol{k}^i \cdot \boldsymbol{E}{\rm d}\boldsymbol{r} = \int \boldsymbol{k}^i \cdot \boldsymbol{L}^i \cdot \boldsymbol{j}^i {\rm d}\boldsymbol{r} = I_K^i Z_{\rm A}^i I_J^i \tag{15}$$

where $I_K^i = \int k_x^i(x=0,y,z) Q_i(y,z)\,{\rm d}y{\rm d}z$ is the total feeder current related to the current $\boldsymbol{k}^i$.

We define a set of basis functions $\phi_n^i, n = 0,1,\cdots N$. We can write the current profile as

$$\boldsymbol{j}^i(\boldsymbol{r}) = \sum_n a_n^i \boldsymbol{\phi}_n^i, \quad \boldsymbol{k}^i(\boldsymbol{r}) = \sum_n b_n^i \boldsymbol{\phi}_n^i. \tag{16}$$

We write

$$I_J^i = \sum_n a_n^i P_n^i, \tag{17}$$

$$I_K^i = \sum_m b_m^i P_m^i, \tag{18}$$

for the current at $y = \pm h, z = z_i$.

So we can write Eq.(15) as

$$\sum_m \sum_n b_m^i L_{mn}^i a_n^i = -Z_{\rm A}^i \sum_m b_m^i P_m^i \sum_n a_n^i P_n^i, \tag{19}$$

here $L_{mn}^i = \int \boldsymbol{\phi}_m^i \cdot \boldsymbol{L}^i \cdot \boldsymbol{\phi}_n^n {\rm d}\boldsymbol{r}$. The operator L_{mn}^i can be obtained from the specific expression for E_y and E_x on the radiating and feeder strap surfaces of the ith antenna respectively. These can be found from Ref.[4]. One can obtain the components of the matrix L_{mn}^i directly from the integral over the ith strap $\int_D \boldsymbol{k}^i \cdot \boldsymbol{E}^i {\rm d}\boldsymbol{r} = \int \boldsymbol{k}_y^i \cdot \boldsymbol{E}_y {\rm d}\boldsymbol{r} + \int \boldsymbol{k}_x^i \cdot \boldsymbol{E}_x {\rm d}\boldsymbol{r}$.

Requiring an extremum, $\delta Z_{\rm A}^i = 0$, we can find the input impedance and the coefficients of the trial functions on the current straps in the same forms as those in Ref.[4], except that we use the superscript i:

$$Z_{\rm A}^i = [\boldsymbol{P}^i \cdot (\boldsymbol{L}^i)^{-1} \cdot \boldsymbol{P}^i]^{-1}, \tag{20}$$

$$\boldsymbol{a}^i = Z_{\rm A}^i [(\boldsymbol{L}^i)^{-1} \cdot \boldsymbol{P}^i], \tag{21}$$

$$\boldsymbol{b}^i = Z_{\rm A}^i [\boldsymbol{P}^i \cdot (\boldsymbol{L}^i)^{-1}], \tag{22}$$

where $Z_{\rm A}^i$ is the ith antenna input impedance, $\boldsymbol{a}^i$ is the vector of the trial function coefficients for physical current and $\boldsymbol{b}^i$ is the vector of the trial function coefficients for the image current on the ith antenna.

3. Results

In this section, for purposes of illustration we analyse the characteristics of an antenna array at 55MHz to the HT-7U plasma with the following parameters: the major radius at the magnetic axis $R = 1.75$m, minor radius $r = 0.4$m, magnetic field at the axis B_0=3.5T, 10% H − 90%D. The plasma electron density profile was taken as Ref.[4]. At $x = d$, we assume a low edge density of n_1, then a linear density profile over a length l_n, a maximum density of n_2 is reached at $x = d + l_n$. In the following, we have chosen $n_1 = 5 \times 10^{12}{\rm cm}^{-3}$, $n_2 = 5 \times 10^{13}{\rm cm}^{-3}$, $l_n = 0.1$m.

The distance of the adjacent toroidal antenna array is 0.05m.

3.1. Dependance on antenna parameter

We consider the dependence of the total antenna impedance on the length of antenna array, the relative location between the return conductor, the central conductor, the Faraday shield and the plasma edge.

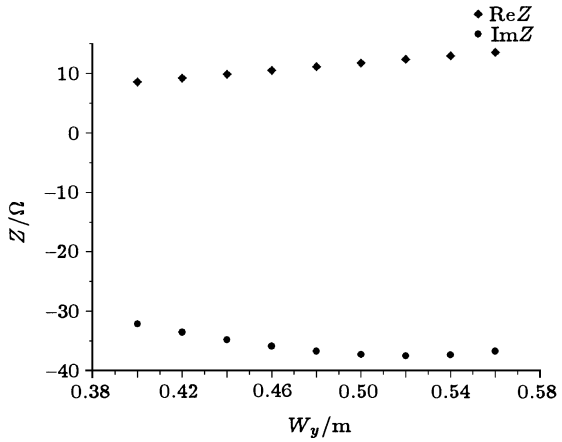


Fig.2. Impedance versus length of antenna. W_z=0.15m, b=0.10m, c=0.14m, d=0.15m.

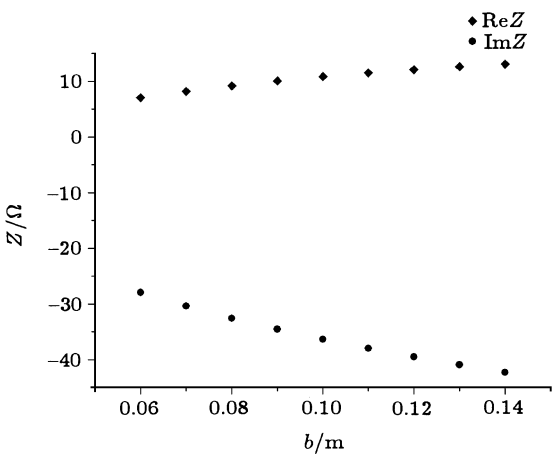


Fig.3. Impedance versus distance b. W_z=0.15m, W_y=0.47m, $c-b$=0.04m, $d-c$=0.01m.

The calculation was performed for 2×2 antenna array for $\alpha = 0$, as is shown in Fig.2 to Fig.5. The real part of the impedance R=ReZ increases as the length of the antenna (Fig.2) and the distance b between the antenna central conductor and the return conductor (Fig.3). ImZ decreases very rapidly in Fig.3 and Fig.4. R reaches maximum value when the distance $c-b$ between the central conductor and the Faraday shield is 1cm (Fig.4), then decreases when $c-b$ increases further. $|\mathrm{Im}Z|$ reaches minimum value when the distance $d-c$ between the plasma edge and the Faraday shield is 10cm(Fig.5).The active impedance increases and reaches maximum value, when $d-c$ increases further, R decreases and finally reaches a constant level (Fig.5).

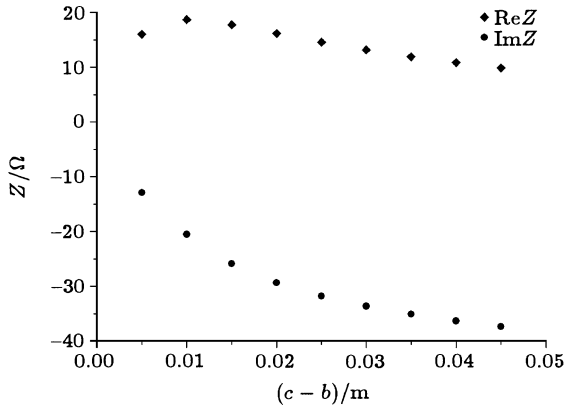


Fig.4. Impedance versus t distance $c-b$. W_z=0.15m, W_y=0.47m, b=0.1, $d-c$=0.04m.

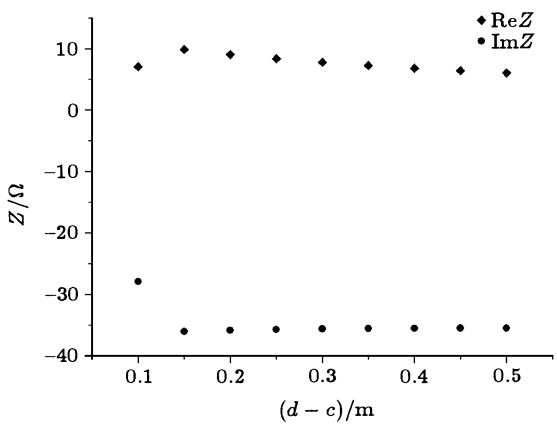


Fig.5. Impedance versus distance $d-c$. W_z=0.15m, W_y=0.47m, b=0.1m, c=0.15m.

3.2. The field structure

The 3-D distribution of the electric field $|E_y|$ along the poloidal and toroidal coordinates at the plasma surface is presented in Figs.6. and 7 for different toroidal phase and α, where the poloidal phase difference is kept at 0°. (θ, φ) means that the toroidal phase difference is θ and the poloidal one is φ. It is clearly seen that the electric field falls off very rapidly away from plasma surface. One can find that the structure of the field at plasma surface more or less corresponds to the antenna current phasings.

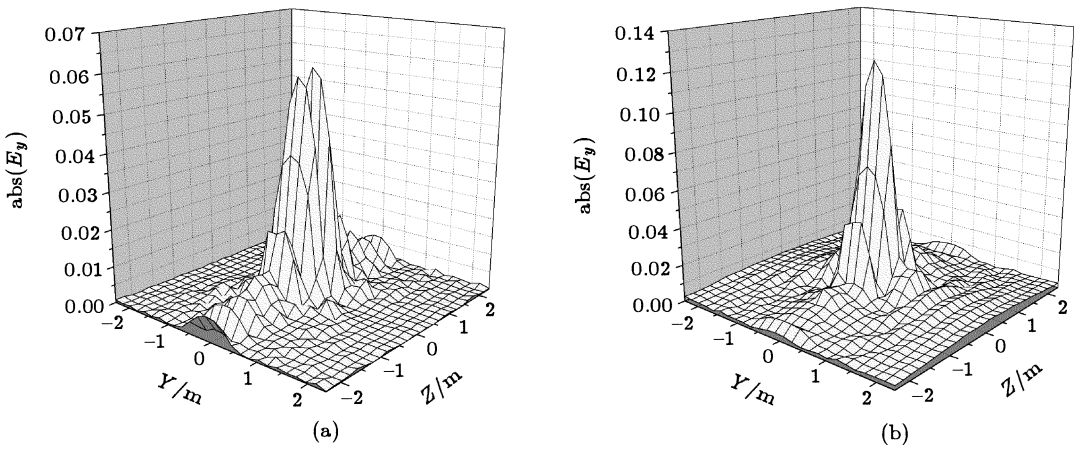


Fig.6. Distribution of $|E_y|$ at the plasma surface: $\alpha = 0$, W_y=0.47m, W_z=0.15m, b=0.10m, c=0.14m, d=0.15m, (a) $(0, \pi)$, (b)(0,0).

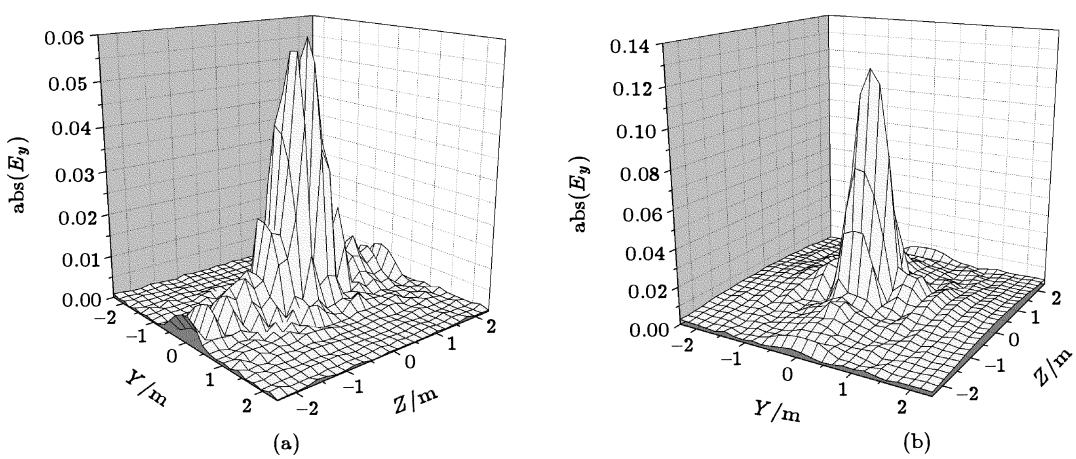


Fig.7. The distribution of $|E_y|$ at the plasma surface: $\alpha = 5°$ same parameters as Fig.6.

4. Conclusion

We applied a general variational formalism derived in Ref.[2], to the antenna array. The extended code can be applied to find the excited wave fields of antenna array. It can also be used as a guide when we optimize design of the ICRF antenna. Practical calculations are given for planed HT-7U ICRF antenna array. The calculations give the requirements for the dimensions of antenna array.

Finally, it should be emphasized that the present work neglects the mutual coupling between adjacent antennas in the model of antenna array.

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