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The Radio Frequency Characteristics of the Combline Antenna

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Abstract

A combline antenna was designed and fabricated to improve the plasma performance of the LHD. It has a capability to drive plasma current and to heat the plasma by ICRF heating. The LHD combline antenna consists of ten antenna elements. The two elements of those are an input and an output antenna element. Equations were derived to examine the RF characteristics. The currents at the Nth antenna element and 1st antenna element were formulated in a 4×4 matrix using the RF current at the RF power supply. A traveling wave was found to be excited at the frequency range as referred to a pass-band. The phase velocity of the traveling wave can be controlled by changing an applied frequency as one of several features of the combline antenna. The width of the pass-band is a function of the value of the plasma loading resistance, the distance between antenna elements, how to feed the RF power and a configuration of the Faraday shields, etc. A T-shaped antenna strap was employed at the present design of the combline antenna, which results in a mixture of the even mode and the odd mode. However the undesirable odd mode can be eliminated by selecting the frequency.

Keywords:

ICRF heating, combline antenna, current drive, helical system, high harmonic heating

1. Introduction

The combline antenna was designed and fabricated, and will be installed into the large helical device (LHD) at the sixth experimental campaign (2002). The combline antenna is expected to achieve two main objectives; one is to drive a current to obtain MHD stability at the high beta plasma and the other is to conduct higher harmonic ion cyclotron rage of frequency (ICRF) heating. It has some advantages; 1) use of mutual coupling of a traveling wave, 2) vacuum feed-throughs required only for end antenna straps, 3) easiness to obtain an impedance matching, 4) wide pass-band, 5) controllability of parallel wave number with frequency. In this paper, the radio frequency (RF) characteristics of the combline antenna are described.

2. Modeling

Decomposed parts of the LHD combline antenna element are shown in Fig. 1; they are a back-plate, Faraday shields (Mo) and a T-shaped antenna strap. A schematic drawing of the comline antenna array is shown in Fig. 2. Two antenna elements on both sides of the array are an inlet antenna element and an outlet antenna element, into which the coaxial transmission line from the LHD vacuum port is connected. The

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equivalent circuit of the LHD combline antenna is shown in Fig. 3. It consists of the two end-elements and the eight middle-elements, which are the same. There are two resonance frequencies referred to as an even mode ω_e and an odd mode ω_o, which is caused by the support of the antenna. These frequencies are calculated as $\omega_e=1/\sqrt{LC}$ and $\omega_0=1/\sqrt{(L+2L_C)C}$ using the inductance, L and the capacitance, C of the antenna and the inductance of the support of the antenna, L_c. The even mode is more preferable in the view point of the effective RF wave penetration beyond an R-cut off layer; therefore it is thought that the elimination of the odd mode with an applied frequency is an important issue.

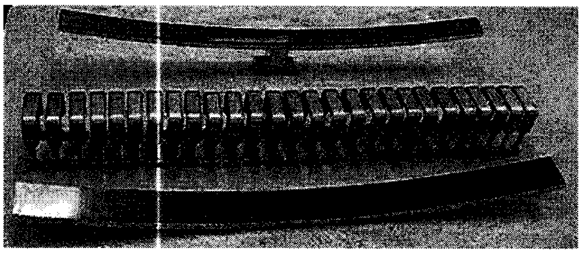

Fig. 1 Decomposed parts of the LHD combline antenna element.

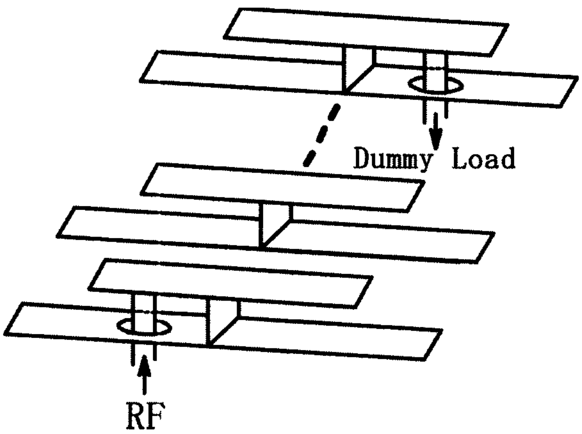

Fig. 2 Schematic drawing of the comline antenna array.

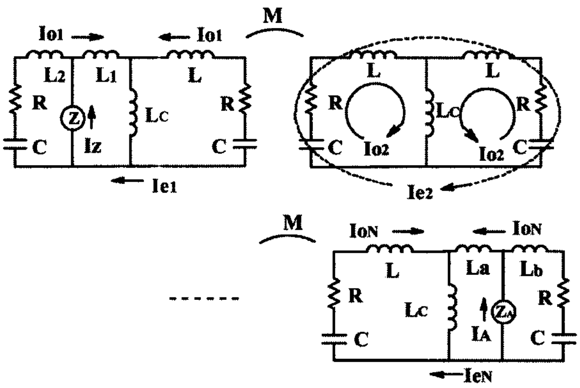

Fig. 3 Equivalent circuit of the LHD combline antenna.

3. Calculation

At the 1st antenna element, the equations of Kirchhoff's law was applied on the left hand and the right hand of the support (see Fig. 3) taking into account of a mutual coupling from the adjacent antenna element. The mutual inductances of the even mode and the odd mode are expressed as M_{ee} and M_{oo}, respectively.

$$0=\left(R+\mathrm{i}\omega L+\frac{1}{\mathrm{i}\omega C}\right)\left(L_{e.1}+I_{o.1}\right)+2\mathrm{i}\omega L_c I_{o.1} + \left(\mathrm{i}\omega L_1+\mathrm{i}\omega L_C\right)I_z+\mathrm{i}\omega M_{ee}I_{e.2} + \mathrm{i}\omega M_{oo}I_{o.2}$$

$$0=\left(R+\mathrm{i}\omega L+\frac{1}{\mathrm{i}\omega C}\right)\left(L_{e.1}-I_{o.1}\right)-2\mathrm{i}\omega L_c I_{o.1} - \mathrm{i}\omega L_C I_z+\mathrm{i}\omega M_{ee}I_{e.2}-\mathrm{i}\omega M_{oo}I_{o.2}\,. \qquad (1)$$

Here, R is a resistance including an Ohmic loss of the antenna element and a plasma loading. $I_{e.i}$ and $I_{o.i}$ are the currents of even mode and of the odd mode at the i^{th} antenna element, and I_Z is the current at the RF power supply at the 1st antenna element. From above two equations, equations for the even mode and the odd mode are obtained as follows;

$$0=2t_e I_{e.1}+\tilde{L}_1 I_z+2\tilde{M}_{ee}I_{e.2}$$

$$0=2t_o I_{o.1}+\left(\tilde{L}_1+2L_C\right)I_z+2\tilde{M}_{oo}I_{o.2} \qquad (2)$$

where

$$\tilde{L}=\mathrm{i}\omega L,\ \tilde{C}=\mathrm{i}\omega C,\ \tilde{M}_{ee}=\mathrm{i}\omega M_{ee},\ \tilde{M}_{oo}=\mathrm{i}\omega M_{oo},$$

$$t_e=R+\tilde{L}+\frac{1}{\tilde{C}},\ t_o=R+\tilde{L}+2\tilde{L}_C+\frac{1}{\tilde{C}}\,.$$

In the similar way, the following equations were obtained at the 2nd element, k^{th} element ($3\le k\le N-2$), $(N-1)^{th}$ element, and N^{th} element, respectively

$$0=2t_e I_{e.2}+2\tilde{M}_{ee}\left(I_{e.1}+I_{e.3}\right)+\tilde{M}_z I_z$$
$$0=2t_o I_{o.2}+2\tilde{M}_{oo}\left(I_{o.1}+I_{o.3}\right)+\tilde{M}_z I_z \qquad (3)$$

$$0=2t_e I_{e.k}+2\tilde{M}_{ee}\left(I_{e.k-1}+I_{e.k+1}\right)$$
$$0=2t_o I_{o.k}+2\tilde{M}_{oo}\left(I_{o.k-1}+I_{o.k+1}\right) \qquad (4)$$

$$0 = 2t_{\mathrm{e}} I_{\mathrm{e}.N-1} + 2\tilde{M}_{\mathrm{ee}}\left(I_{\mathrm{e}.N-2} + I_{\mathrm{e}.N}\right) - \tilde{M}_{\mathrm{A}} I_{\mathrm{A}}$$
$$0 = 2t_{\mathrm{o}} I_{\mathrm{o}.N-1} + 2\tilde{M}_{\mathrm{oo}}\left(I_{\mathrm{o}.N-2} + I_{\mathrm{o}.N}\right) + \tilde{M}_{\mathrm{A}} I_{\mathrm{A}} \qquad (5)$$

$$0 = 2t_{\mathrm{e}} I_{\mathrm{e}.N} + 2\tilde{M}_{\mathrm{ee}} I_{\mathrm{e}.N-1} - \tilde{L}_{\mathrm{a}} I_{\mathrm{A}}$$
$$0 = 2t_{\mathrm{o}} I_{\mathrm{o}.N} + 2\tilde{M}_{\mathrm{oo}} I_{\mathrm{o}.N-1} + \left(\tilde{L}_{\mathrm{a}} + 2\tilde{L}_{\mathrm{C}}\right) I_{\mathrm{A}} \qquad (6)$$

where, $\tilde{M}_{\mathrm{Z}}=\mathrm{i}\omega M_{\mathrm{Z}}$, $\tilde{M}_{\mathrm{A}}=\mathrm{i}\omega M_{\mathrm{A}}$.

Here M_{Z} and M_{A} are mutual inductances at the RF power supply and at the RF power output connected to the dummy load, and I_{A} is a current at the output transmission line. Therefore the output impedance Z_{A} and the input impedance Z are expressed as follows.

$$Z I_{\mathrm{Z}} = -t_2\left(I_{\mathrm{e}.1} + I_{\mathrm{o}.1}\right)$$
$$Z_{\mathrm{A}} I_{\mathrm{A}} = -t_{\mathrm{b}}\left(I_{\mathrm{e}.N} - I_{\mathrm{o}.N}\right) \qquad (7)$$

where

$$t_2 = R + \tilde{L}_2 + \frac{1}{\tilde{C}}, \qquad t_{\mathrm{b}} = R + \tilde{L}_{\mathrm{b}} + \frac{1}{\tilde{C}}.$$

Substituting above equations for eqs. (6), the current at the $(N-1)^{\mathrm{th}}$ antenna element is expressed using $I_{\mathrm{e}.N}$ and $I_{\mathrm{o}.N}$.

$$\begin{pmatrix} I_{\mathrm{e}.N-1} \\ I_{\mathrm{o}.N-1} \end{pmatrix} = \begin{pmatrix} U_{11}^{(N-1)} & U_{12}^{(N-1)} \\ U_{21}^{(N-1)} & U_{22}^{(N-1)} \end{pmatrix} \begin{pmatrix} I_{\mathrm{e}.N} \\ I_{\mathrm{o}.N} \end{pmatrix} \qquad (8)$$

where elements of the 2×2 matrix for the $(N-1)^{\mathrm{th}}$ antenna element are

$$U_{11}^{(N-1)} = -\frac{2t_{\mathrm{e}} + \dfrac{\tilde{L}_{\mathrm{a}} t_{\mathrm{b}}}{Z_{\mathrm{A}}}}{2\tilde{M}_{\mathrm{ee}}}, \quad U_{12}^{(N-1)} = \frac{\dfrac{\tilde{L}_{\mathrm{a}} t_{\mathrm{b}}}{Z_{\mathrm{A}}}}{2\tilde{M}_{\mathrm{ee}}}$$

$$U_{21}^{(N-1)} = -\frac{\dfrac{\left(2\tilde{L}_{\mathrm{C}} + \tilde{L}_{\mathrm{a}}\right) t_{\mathrm{b}}}{Z_{\mathrm{A}}}}{2\tilde{M}_{\mathrm{oo}}},$$

$$U_{22}^{(N-1)} = \frac{2t_{\mathrm{o}} + \dfrac{\left(2\tilde{L}_{\mathrm{C}} + \tilde{L}_{\mathrm{a}}\right) t_{\mathrm{b}}}{Z_{\mathrm{A}}}}{2\tilde{M}_{\mathrm{oo}}}.$$

The currents at the $(N-2)^{\mathrm{th}}$ antenna element is obtained by substituting eqs. (8) for eqs. (5).

$$\begin{pmatrix} I_{\mathrm{e}.N-2} \\ I_{\mathrm{o}.N-2} \end{pmatrix} = \begin{pmatrix} U_{11}^{(N-2)} & U_{12}^{(N-2)} \\ U_{21}^{(N-2)} & U_{22}^{(N-2)} \end{pmatrix} \begin{pmatrix} I_{\mathrm{e}.N} \\ I_{\mathrm{o}.N} \end{pmatrix} \qquad (9)$$

where elements of the 2×2 matrix for the $(N-2)^{\mathrm{th}}$ are

$$U_{11}^{(N-2)} = -\frac{2t_{\mathrm{e}} U_{11}^{(N-1)} + 2\tilde{M}_{\mathrm{ee}} + \dfrac{\tilde{M}_{\mathrm{A}} t_{\mathrm{b}}}{Z_{\mathrm{A}}}}{2\tilde{M}_{\mathrm{ee}}}$$

$$U_{12}^{(N-2)} = -\frac{2t_{\mathrm{e}} U_{12}^{(N-1)} - \dfrac{\tilde{M}_{\mathrm{A}} t_{\mathrm{b}}}{Z_{\mathrm{A}}}}{2\tilde{M}_{\mathrm{ee}}}$$

$$U_{21}^{(N-2)} = -\frac{2t_{\mathrm{o}} U_{21}^{(N-1)} - \dfrac{\tilde{M}_{\mathrm{A}} t_{\mathrm{b}}}{Z_{\mathrm{A}}}}{2\tilde{M}_{\mathrm{oo}}}$$

$$U_{22}^{(N-2)} = -\frac{2t_{\mathrm{o}} U_{21}^{(N-1)} + 2\tilde{M}_{\mathrm{oo}} + \dfrac{\tilde{M}_{\mathrm{A}} t_{\mathrm{b}}}{Z_{\mathrm{A}}}}{2\tilde{M}_{\mathrm{oo}}}.$$

Here two recurrence formulas for both modes at the k^{th} antenna element (see eq. (4)) were solved. The currents at the 3rd element and the 2nd element were calculated using I_{N-1} and I_{N-2} in the following formulas.

$$\begin{pmatrix} I_{\mathrm{e}.3} \\ I_{\mathrm{o}.3} \end{pmatrix} = \begin{pmatrix} U_{11}^{(3)} & U_{12}^{(3)} \\ U_{21}^{(3)} & U_{22}^{(3)} \end{pmatrix} \begin{pmatrix} I_{\mathrm{e}.N} \\ I_{\mathrm{o}.N} \end{pmatrix}$$
$$\begin{pmatrix} I_{\mathrm{e}.2} \\ I_{\mathrm{o}.2} \end{pmatrix} = \begin{pmatrix} U_{11}^{(2)} & U_{12}^{(2)} \\ U_{21}^{(2)} & U_{22}^{(2)} \end{pmatrix} \begin{pmatrix} I_{\mathrm{e}.N} \\ I_{\mathrm{o}.N} \end{pmatrix} \qquad (10)$$

where

$$U_{11}^{(3)} = H_{\mathrm{e}1} U_{11}^{(N-2)} - H_{\mathrm{e}2} U_{11}^{(N-1)}$$
$$U_{12}^{(3)} = H_{\mathrm{e}1} U_{12}^{(N-2)} - H_{\mathrm{e}2} U_{12}^{(N-1)}$$
$$U_{21}^{(3)} = H_{\mathrm{o}1} U_{21}^{(N-2)} - H_{\mathrm{o}2} U_{21}^{(N-1)}$$
$$U_{22}^{(3)} = H_{\mathrm{o}1} U_{22}^{(N-2)} - H_{\mathrm{o}2} U_{22}^{(N-1)}$$
$$U_{11}^{(2)} = F_{\mathrm{e}1} U_{11}^{(N-2)} - F_{\mathrm{e}2} U_{11}^{(N-1)}$$
$$U_{12}^{(2)} = F_{\mathrm{e}1} U_{12}^{(N-2)} - F_{\mathrm{e}2} U_{12}^{(N-1)}$$
$$U_{21}^{(2)} = F_{\mathrm{o}1} U_{21}^{(N-2)} - F_{\mathrm{o}2} U_{21}^{(N-1)}$$
$$U_{22}^{(2)} = F_{\mathrm{o}1} U_{22}^{(N-2)} - F_{\mathrm{o}2} U_{22}^{(N-1)}$$

$$F_{\mathrm{e}1} = \frac{\beta_{\mathrm{e}}^{N-3} - \alpha_{\mathrm{e}}^{N-3}}{\beta_{\mathrm{e}} - \alpha_{\mathrm{e}}}, \quad F_{\mathrm{e}2} = \frac{\alpha_{\mathrm{e}}\beta_{\mathrm{e}}^{N-3} - \alpha_{\mathrm{e}}^{N-3}\beta_{\mathrm{e}}}{\beta_{\mathrm{e}} - \alpha_{\mathrm{e}}}$$
$$F_{\mathrm{o}1} = \frac{\beta_{\mathrm{o}}^{N-3} - \alpha_{\mathrm{o}}^{N-3}}{\beta_{\mathrm{o}} - \alpha_{\mathrm{o}}}, \quad F_{\mathrm{o}2} = \frac{\alpha_{\mathrm{o}}\beta_{\mathrm{o}}^{N-3} - \alpha_{\mathrm{o}}^{N-3}\beta_{\mathrm{o}}}{\beta_{\mathrm{o}} - \alpha_{\mathrm{o}}}$$

$$H_{\mathrm{e}1} = \frac{\beta_{\mathrm{e}}^{N-4} - \alpha_{\mathrm{e}}^{N-4}}{\beta_{\mathrm{e}} - \alpha_{\mathrm{e}}}, \quad H_{\mathrm{e}2} = \frac{\alpha_{\mathrm{e}}\beta_{\mathrm{e}}^{N-4} - \alpha_{\mathrm{e}}^{N-4}\beta_{\mathrm{e}}}{\beta_{\mathrm{e}} - \alpha_{\mathrm{e}}}$$
$$H_{\mathrm{o}1} = \frac{\beta_{\mathrm{o}}^{N-4} - \alpha_{\mathrm{o}}^{N-4}}{\beta_{\mathrm{o}} - \alpha_{\mathrm{o}}}, \quad H_{\mathrm{o}2} = \frac{\alpha_{\mathrm{o}}\beta_{\mathrm{o}}^{N-4} - \alpha_{\mathrm{o}}^{N-4}\beta_{\mathrm{o}}}{\beta_{\mathrm{o}} - \alpha_{\mathrm{o}}}.$$

Here α_{e} and β_{e} are solutions of the recurrence formula of the even mode, and α_{o} and β_{o} are those of the odd mode. α and β are parameters to characterize the forward and backward traveling waves.

$$\alpha_e = -\frac{-t_e + \sqrt{t_e^2 - 4M_{ee}^2}}{2M_{ee}}, \quad \beta_e = -\frac{-t_e - \sqrt{t_e^2 - 4M_{ee}^2}}{2M_{ee}}$$

$$\alpha_o = -\frac{-t_o + \sqrt{t_o^2 - 4M_{oo}^2}}{2M_{oo}}, \quad \beta_o = -\frac{-t_o - \sqrt{t_o^2 - 4M_{oo}^2}}{2M_{oo}}.$$

Using all above equations, $I_{e.N}$ and $I_{o.N}$ were expressed by I_Z. A formula to relate $I_{e.1}$, $I_{o.1}$, $I_{e.N}$ and $I_{o.N}$, to I_Z was established in the following equation using a 4×4 matrix;

$$\begin{pmatrix} L_{e.1} \\ L_{o.1} \\ L_{e.N} \\ L_{o.N} \end{pmatrix} = \begin{pmatrix} 2t_e & 0 & 2\tilde{M}_{ee}U_{11}^{(2)} & 2\tilde{M}_{ee}U_{12}^{(2)} \\ 0 & 2t_o & 2\tilde{M}_{oo}U_{21}^{(2)} & 2\tilde{M}_{oo}U_{22}^{(2)} \\ 2\tilde{M}_{ee} & 0 & 2t_e U_{11}^{(2)} + 2\tilde{M}_{ee}U_{11}^{(3)} & 2t_e U_{12}^{(2)} + 2\tilde{M}_{ee}U_{12}^{(3)} \\ 0 & 2\tilde{M}_{oo} & 2t_o U_{21}^{(2)} + 2\tilde{M}_{oo}U_{21}^{(3)} & 2t_o U_{22}^{(2)} + 2\tilde{M}_{oo}U_{22}^{(3)} \end{pmatrix}^{-1} \begin{pmatrix} -\tilde{L}_1 I_Z \\ -(\tilde{L}_1 + 2\tilde{L}_C)I_Z \\ -\tilde{M}_1 I_Z \\ -\tilde{M}_Z I_Z \end{pmatrix}. \tag{11}$$

4. RF Characteristics of LHD Combline Antenna

The LHD combline antenna has ten elements; the characteristics of the combline antenna are examined in the case of N=10 and in an adequate case; L=9×10^{-8} [H], L_1=L_2=L_a=L_b=4.5×10^{-8} [H], L_c=M_{ee}=M_{oo}=9×10^{-9} [H], C=50×10^{-12} [F], R=0.5 [Ω], M_Z=M_A=3×10^{-9} [H], and Z_A=50 [Ω]. A real and an imaginary part of Z are plotted as a function of ω/ω_0 in Fig. 4. ω_0 is a resonant frequency of the even mode of the antenna element. The real part of Z is found around 50 Ω at the region between 0.85<ω/ω_0<1.2, which is called a pass-band. A high RF power can be injected to the LHD plasma via the combline antenna with a relatively low RF voltage and a traveling wave can be driven in the plasma within this bandwidth. The bandwidth becomes wider with the increase in R or the decrease in C. It can be also changed by the distance between elements, how to feed the RF power, a configuration of the Faraday shields and so on.

A resonant frequency of the even mode $\omega_e/2\pi$ is selected at 75 MHz; however taking into account a mutual inductance, a good condition where the even mode dominates over the odd mode is obtained at the a little higher frequency than 75 MHz. A decay of the current across each antenna element is shown in Fig. 5, where the frequency is employed at 76 MHz. As the value of the loading resistance R increases, the difference between the adjacent antenna elements becomes smaller and the decay length of the current becomes shorter.

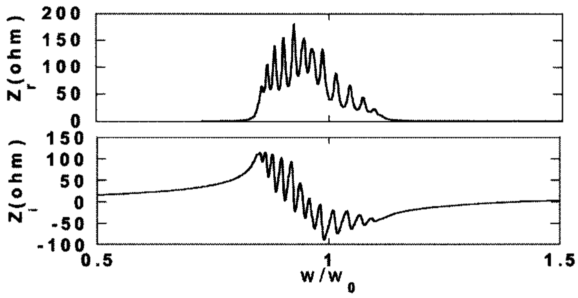

Fig. 4 A Real and imaginary part of Z as a function of ω/ω_0.

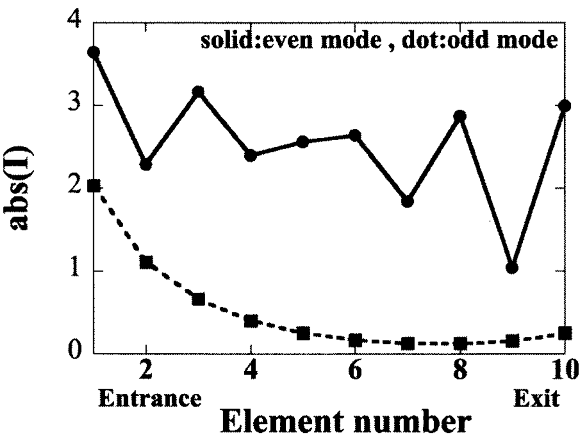

Fig. 5 Current across each antenna element at f = 76 MHz.

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