Characteristics of a Complex-Conjugate Impedance Antenna System for ICRF Heating

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Characteristics of a complex-conjugate impedance antenna system for ICRF (ion cyclotron resonance frequency) heating are discussed in this paper. Large RF power is reflected in such transition as that of ELMy H-L mode because of the big change in the plasma resistance for ICRF heating. In such a case the RF power injection to the plasma is ceased to protect the tetrode vacuum tubes. The idea of a complex-conjugate impedance antenna system to mitigate the large reflected RF power has been recently proposed. In this system the RF power is split at a T-junction and supplied to two identical ICRF antennas. The imaginary part of the complex impedance at the T-junction can be eliminated, which is the main feature of this system. The length of the transmission lines connected to both antennas can be finely tuned to realize a complex-conjugate relation for the two impedances. The reflected RF power fraction can be reduced in the wide range of plasma resistance which occurs in the ELMy H-L mode transition.

Keywords: ICRF heating, impedance matching system, H-L mode transition, reflected RF power fraction

1. Introduction

H-mode plasma operation is absolutely desirable for ITER and future fusion reactors. However the ICRF (ion cyclotron range of frequency) heating and current drive have the serious problem in ELMy H-L mode transition that large RF power is reflected due to the big change in the plasma impedance. In such a case the injection of RF power to the plasma is ceased to protect the tetrode vacuum tubes. Many ideas to improve the ELMy tolerance in the ICRF heating system have been proposed, and trials have been carried out in plasma experimental devices: employing a 3dB 90º hybrid junction [1, 2] and a frequency feedback control [3] etc. In this report we discuss a complex conjugate antenna system for the ICRF heating. It has been recently proposed and studied [4, 5] and has become a strong candidate for use as the ITER ICRF antenna system. The conjugate antenna system is derived from a conventional single stub tuner. The RF power is divided into two at a T-junction in the transmission line and is supplied to two identical antennas as shown in Fig.1. A feature of this system is that the complex impedance at the T-junction can be limited to only the real part by adjusting the lengths between both the antennas and the T-junction. The imaginary part of the resultant impedance at the T-junction can be made zero, specifically when the sum of the lengths of the transmission lines is made just half of the RF wave-length. This is the reason why the system is called the complex-conjugate antenna system. The reflected RF power fraction can be reduced to about 10% by optimizing it even in the presence of large resistance change, such as that of the ELMy H-L mode transition. The reflected RF power fraction would have been more than 30% in the conventional single stub tuner system.

2. The Conjugate Antenna System

The conjugate antenna system consists of two antennas connected by separate transmission lines, as shown in Fig.1. An ICRF heating power is divided in two at the T-junction and fed to each antenna. The signs of the imaginary parts of the impedances at the T-junction can be made opposite to each other by selecting proper lengths between the T-junction and the antennas. For the ICH antenna-1 as shown in Fig.1 the RF voltage and current at the T-junction are defined as V_C and I_{C1}, respectively. The normalized length between the T-junction and the ICH antenna is defined as A_{AC1}. The RF voltage and current at the ICH antenna are defined as V_{R1} and I_{R1}, respectively as

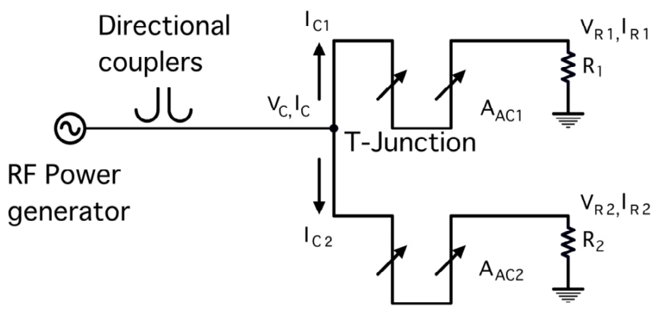

Fig.1 Schematic drawing of conjugate antenna impedance matching system.

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also shown in Fig.1. The resistance of the ICH antenna R_1 is expressed by the ratio of V_{R1} to I_{R1}. The relation of V_C and I_{C1} to V_{R1} and I_{R1} is expressed in the following equation:

$$\begin{pmatrix} V_c \\ I_{c1} \end{pmatrix} = \begin{pmatrix} \cos(2\pi A_{AC1}) & jZ_0 sin(2\pi A_{AC1}) \\ j/Z_0 sin(2\pi A_{AC1}) & \cos(2\pi A_{AC1}) \end{pmatrix} \begin{pmatrix} V_{R1} \\ I_{R1} \end{pmatrix} \quad (1)$$

Then I_{C1} is formulated in the following equation:

$$I_{C1} = \frac{jR_1/Z_0(sin 2\pi A_{AC1}) + \cos(2\pi A_{AC1})}{R_1\cos(2\pi A_{AC1}) + jZ_0 sin(2\pi A_{AC1})} V_C$$

In a similar way for the ICH antenna-2 I_{C2} can be easily obtained by changing the suffix 1 to suffix 2 and employing A_{AC2}. At the T-junction the RF current I_C is the summation of I_{C1} and I_{C2}, and the impedance Z is the ratio of V_C to I_C. Then the impedance Z can be expressed in the following equation:

$$\begin{aligned} Z &= \frac{V_C}{I_C} = \frac{V_C}{I_{C1} + I_{C2}} = \frac{A + jB}{C + jD} \\ A &= R_1R_2 - Z_0^2 tan(2\pi A_{AC1}) tan(2\pi A_{AC2}) \\ B &= Z_0\left\{R_2 tan(2\pi A_{AC1}) + R_1 tan(2\pi A_{AC2})\right\} \\ C &= (R_1 + R_2)\left\{1 - tan(2\pi A_{AC1}) tan(2\pi A_{AC2})\right\} \\ D &= (R_1R_2/Z_0 + Z_0)\left\{tan(2\pi A_{AC1}) + tan(2\pi A_{AC2})\right\} \end{aligned} \quad (2)$$

To simplify the above equation the resistance of R_2 is here assumed to be the same as R_1 and the relation of $\tan(2\pi A_{AC1})$=- $\tan(2\pi A_{AC2})$ is employed for the requirement of the complex- conjugate of the impedance Z. Then

$$Z = \frac{R^2 + Z_0^2 tan^2(2\pi A_{AC})}{2R\left\{1 + tan^2(2\pi A_{AC})\right\}} \quad (3)$$

Here $R=R_1$ and $A_{AC}=A_{AC1}$. The impedance Z is normalized by the characteristic impedance of the transmission line Z_0,

$$\frac{Z}{Z_0} = \frac{R_N^2 + tan^2(2\pi A_{AC})}{2R_N\left\{1 + tan^2(2\pi A_{AC})\right\}} \quad (4)$$

Here R_N is also the normalized resistance by Z_0, i.e., $R_N=R/Z_0$. The impedance matching condition can be obtained at $Z/Z_0=1$. Then two solutions of R_{N0} and R_{N1} are derived for A_{AC} because the above equation is a quadratic equation for R_N as follows

$$\begin{aligned} R_{N0}, R_{N1} &= 1 + tan^2(2\pi A_{AC}) \\ &\pm \left\{1 + tan^2(2\pi A_{AC}) + tan^4(2\pi A_{AC})\right\}^{1/2} \quad (5) \\ R_{N0}\cdot R_{N1} &= tan^2(2\pi A_{AC}) \end{aligned}$$

The two solutions of R_{N0} and R_{N1} are plotted in solid and dashed lines against A_{AC}, As shown in Fig.2. When R_N is increased, A_{AC} becomes larger. It is found that R_{N1} is larger than 2. The plasma resistance is usually measured around 2~8$_W$, i.e., R_{N0}=0.04~0.16, therefore A_{AC}=0.04~0.09 as seen in Fig.2

2. Reflected power fraction in wide range of R_N

In this section the dependence of the reflected

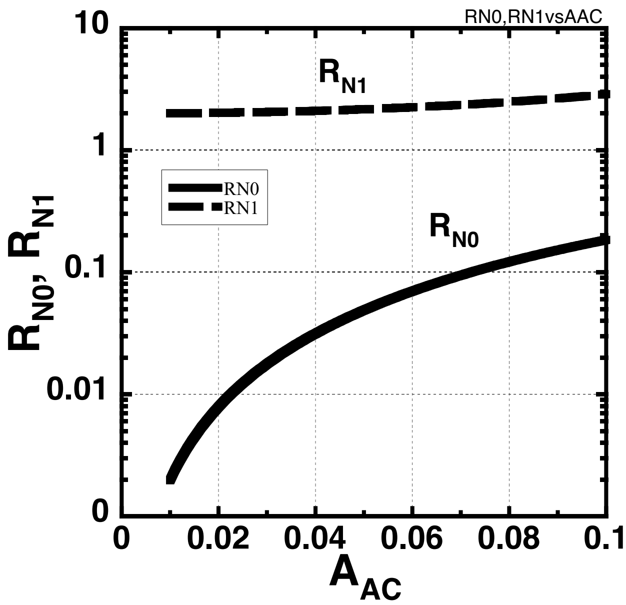

Fig.2 Impedance matching condition in conjugate antenna system: two solutions of R_{N0} and R_{N1} vs. normalized length A_{AC}.

power fraction on the wide range of RN is researched with the aim of reducing the reflected power fraction in the H-L mode transition. It is expected that the reflected power fraction can be reduced employing the conjugate antenna system because there is no imaginary part in the impedance. In addition the performance of the new system is compared with that of the conventional single stub tuner. The reflected power fraction can be calculated using the impedance at the T-junction as seen in eq.(4). By substituting a term of tangent of eq.(5), i.e., $R_{N0}\cdot R_{N1} = tan^2(2\pi A_{AC})$ to eq.(4), then the following equation is derived:

$$\begin{aligned} \frac{Z}{Z_0} &= \frac{R_N^2 + R_{N0}R_{N1}}{2R_N(1 + R_{N0}R_{N1})} = E \\ \frac{\partial E}{\partial R_N} &= \frac{1}{2(1 + R_{N0}R_{N1})}\left(1 - \frac{R_{N0}R_{N1}}{R_N^2}\right) \end{aligned} \quad (6)$$

It is needless to say that when the value of the first equation becomes one, it is the impedance matching condition at $R_N=R_{N0}$ and R_{N1}. In addition when $R_N^2=R_{N0}R_{N1}$, the value of the second equation becomes zero and E has the maximum deviated value from one, which will be discussed in detail in section 4. The reflected RF power fraction R_{ref} can be calculated at any R_N using the above E in the following equation;

$$R_{ref} = \left(\frac{E - 1}{E + 1}\right)^2 \quad (7)$$

Then it is easily predicted that the reflected power fraction has its local maximum between R_{N0} and R_{N1}.

3. Comparison of the Conjugate Antenna System with the Single Stub Tuner System

The dependence of the reflected RF power fraction on variable resistance in the conjugate antenna system is compared with that in the single stub tuner. As previously described the conjugate antenna system is derived from a conventional single stub tuner. The abscissa and the ordinate of Fig.3 are the normalized resistance $R_N=R/Z_0$ and the reflected RF power fraction R_{ref}, respectively. In this case impedance matching is obtained at $R_{N0}=0.044$ in both cases. Here the assumed range of varying R_N is plotted with the arrow, i.e., $R_N=0.04\sim0.16$, which can be estimated from the data measured in the ELMy plasma on JET [6]. It is easily found that improvement is not seen in the smaller normalized resistance, i.e., $R_N<R_{N0}$, but that a reduction of the reflected RF power fraction in the conjugate antenna system is larger at the large normalized resistance, i.e., $R_{N0}<R_N$, as seen in Fig.3. The superiority of the conjugate antenna system to the conventional single stub tuner system is recognized, but in the range of $0.046<R_N<0.16$ the reflected power fraction has the maximum of 22%, which exceeds the allowable level to the vacuum tetrode tube, i.e., 5%. Therefore further development is required.

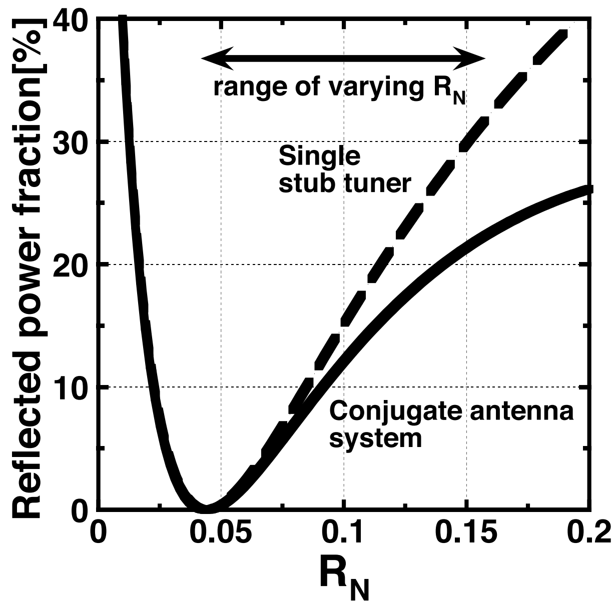

Fig.3 Comparison of reflected RF power fraction in conjugate antenna system with that in single stub tuner. Solid and dashed lines are that in conjugate antenna system and in single stub tuner, respectively. The impedance matching is obtained at the normalized resistance of $R_{N0}=0.044$ in both cases.

4. Improved Performance in the Conjugate Antenna System

As seen in eqs.(6) and (7) the reflected power fraction R_{ref} becomes zero at $R_N=R_{N0}$ and R_{N1}. It is easily understood that R_{ref} has its local maximum at R_{Nm} between the two solutions. The value of R_{Nm} is found by $dE/dR_N=0$ as seen in eq.(6),

$$R_{Nm}=(R_{N0}R_{N1})^{1/2} \tag{8}$$

R_{Nm} is a geometric mean of R_{N0} and R_{N1}. As seen in eq. (5) R_{N1} is a function of R_{N0} and then R_{refmax} is transformed to a function of only R_{N0}. When $dR_{refmax}/dR_{N0}=0$, R_{refmax} can be minimized, and the value of R_{N0} is found from the following relation.

$$R_{N0}^4-5R_{N0}^3+6R_{N0}^2-5R_{N0}+1=0 \tag{9}$$

Then R_{N0} and R_{Nm} are determined as $R_{N0}=0.268$ and $R_{Nm}=1.0$. In this case, the value of E becomes 0.5 and the minimized R_{refmax} is calculated to be 11.1% as seen in Fig.4. In Fig.4 R_{refmax} is plotted against R_{N0} as well as R_{N1} and R_{Nm}. It is found that R_{Nm} increases with R_{N0}, and R_{refmax} decreases with R_{N0}, and that the minimized P_{refmax} is 11.1% at $R_{N0}=0.268$ and $R_{Nm}=1.0$ as shown in Fig.4. Therefore the best performance of the conjugate antenna system is obtained at $R_{N0}=0.268$ and the maximum reflected power fraction can be reduced to 11.1% over the very wide range of $0.0268<R_N<3.5$.

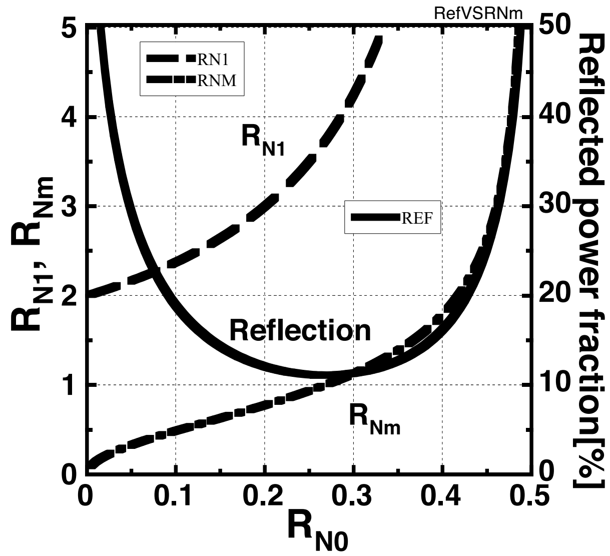

Fig.4 Dependences of R_{N1}, R_{Nm} and the maximum reflected power fraction P_{refmax} at R_{Nm} on R_{N0}. The minimized P_{refmax} can be reduced to 11.1% at $R_{N0}=0.268$.

The dependence of R_{ref} on R_N is shown in Fig.5 as the best performance of the conjugate antenna system. Here at $R_{N0}=0.268$ R_{ref} is calculated in the range of $0.01<R_N<2.0$. The R_{ref} has its maximum of 11.1% at $R_{Nm}=1.0$ and decreases with R_N. In this figure the dependence of R_{ref} on R_N in the single stub tuner is also plotted with the dashed line. The variable range of R_N is plotted using the arrow, which can be estimated using data measured in the H-L mode transition as previously described and in which R_{N0} and R_{Nm} correspond to H-mode and L-mode plasma resistance, respectively. In this range R_{refmax} can be suppressed to 11.1%, but is 33% in the single stub tuner system.

5. RF Power Capability in the Lower Characteristic Impedance Transmission Line

As previously described, the measured plasma resistance ranged from 2Ω to 8Ω during the H-L mode transition. Therefore if this conjugate antenna system is applied to the H-L mode transition plasma, a lower characteristic impedance of the transmission line such as Z_0=7.46Ω should be employed. When the outer diameter of a transmission line is constant, the clearance between the inner and the outer transmission line becomes smaller with the decrease in the characteristic impedance. If it is assumed that the maximum RF stand-off voltage is proportional to the clearance, the maximum RF power capability to be transmitted at Z_0 is assessed in the following equation:

$$P_{RF\max} \propto \left(\frac{10^{Z_0/138.22}-1}{Z_0}\right)^2 \qquad (10)$$

Then P_{RFmax} at Z_0=7.46Ω is calculated to be reduced to less than 50% of that at Z_0=50Ω, as seen in Fig.6. It is thought that a transmission line with a larger diameter should be employed for higher ICRF power heating. In accordance with the experimental data so far achieved in our R&D for a steady-state ICRF heating at the MW level [7], it is estimated that the large diameter of 360 mm is required. It is expected that further development will be required to reduce the reflected power fraction over the wide range of the plasma resistance.

6. Conclusions

Our conclusions are summarized as follows:

1) The superiority of the conjugate antenna system was verified, comparing it with the single stub tuner system.

2) In the impedance matching for the conjugate antenna system there are two solutions of the normalized resistance for A_{AC}, i.e., the normalized length between the T-junction and the antenna.

3) The maximum reflected power fraction R_{refmax} is found at the geometric mean of two normalized solutions, i.e., $R_{Nm}=(R_{N0}R_{N1})^{1/2}$. When R_{N0}=0.268 and subsequently R_{Nm}=1.0, R_{refmax} can be minimized to 11.1%.

4) The low characteristic impedance of the co-axial transmission line should be employed, but the transmitted power capability will be lowered as predicted in Fig.6. Therefore a co-axial transmission line with larger diameter should be employed for MW-level heating. Further development is required to reduce the R_{refmax} over the wide range of the plasma resistance as seen in the ELMy H-L mode transition.

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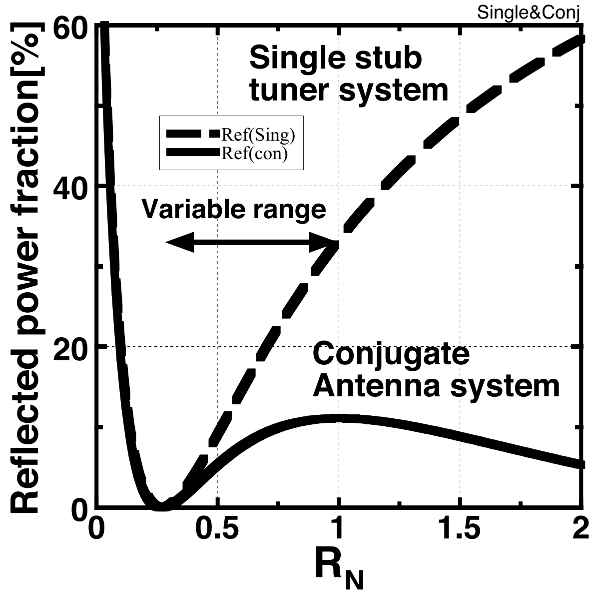

Fig.5 Dependence of the reflected power fraction on R_N in conjugate antenna system (in solid line) and single stub tuner system (in dashed line). The initial impedance matching is obtained at R_{N0}=0.268. Variable range is also plotted with arrow, 0.268<R_N<1.0.

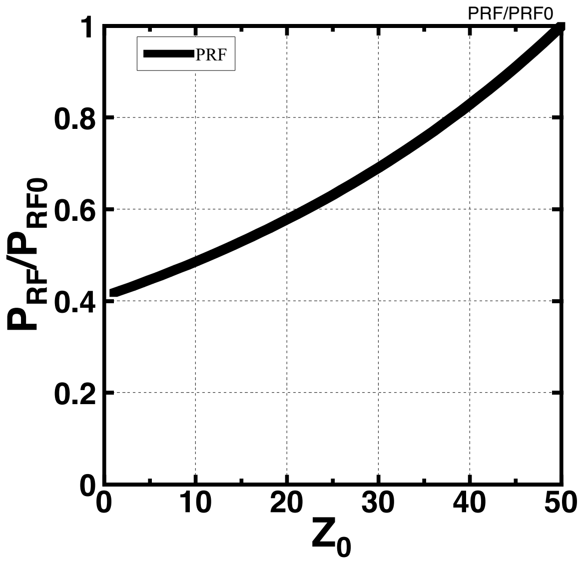

Fig.6 Dependence of the transmitted power capability P_{RF}/P_{RF0} on the characteristic impedance of the co-axial transmission line.