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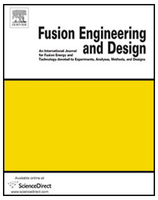

Design of optimized impedance transformer for ICRF antenna in LHD

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HIGHLIGHTS

- We developed optimization method of impedance transformer for ICRF antenna.
- Power loss will be one-third with the optimized impedance transformer.
- Possibility of damage on the transmission line will be drastically reduced.
- High performance will be kept in the wide antenna impedance region.

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ABSTRACT

A pair of ion cyclotron range of frequencies (ICRF) antennas in the large helical device (LHD), HAS antennas showed high efficiency in minority ion heating. However the low loading resistance must be increased to prevent breakdown in transmission line. Moreover, the voltage and the current around the feed-through must be reduced to protect it. For these purpose, we developed a design procedure of the impedance transformer for HAS antennas. To optimize the transformer, the inner conductors were divided into several segments and the radii of them were given discretely and independently. The maximum effective loading resistance was obtained by using all combinations of radii within the limitations of the voltage and current at the feed-through and the electric field on the transformer. To get a precise solution, this procedure was repeated several times by narrowing the range of radii of inner conductors. Then the optimized impedance transformer was designed by smoothing the radii of inner conductors. For the typical discharge, the voltage and current at the feed-through were reduced to the half of the original values with the same power. The effective loading resistance was increased to more than four times. High performance is expected in wide impedance region.

1. Introduction

A pair of ion cyclotron range of frequencies (ICRF) antennas (HAS antennas) [1] were installed in the large helical device (LHD) [2] in 2010, where HAS means HAndShake or HAsuu-Seigyo (wave-number-control in Japanese). These antennas showed high efficiency in minority ion heating by adjusting current phase in center straps; however, there are some issues to be solved. One is the low loading resistance, which increases the voltage on the transmission line. The typical loading resistance for the frequency of 38.5 MHz is 3.5 Ω and the voltage on the transmission line reaches the interlock level of 35 kV with the power of 0.8 MW. The other issues are problems with ceramic feed-through. Once, a ceramic cracked as a result of arcing at feed-through. Moreover, the temperature near the feed-through kept increasing during long pulse discharges; 10 °C/5 min with the voltage on the transmission line of 30 kV. Reduction of the voltage at the feed-through is necessary for the prevention of arcing, and the current around the feed-through must also be reduced to lower Joule heating.

Impedance transformer is the transmission line that adjusts impedance by selecting the length and characteristic impedance properly. A disadvantage of impedance transformers is that the operating frequency is fixed since normally it does not have tuning mechanism. An optimized impedance transformer between antenna head and the feed-through is one of candidates to solve the issues on HAS antennas, which is simpler than the pre-stub tuner in vacuum vessel. We developed a design procedure of the impedance transformer and applied it to HAS antenna. In Section 2, the optimization method of the impedance transformer is described. In Section 3, the impedance transformer for HAS antenna is optimized. The high performance in wide impedance region is shown in Section 4, and we summarize the performance of upgraded transmission line in Section 5.

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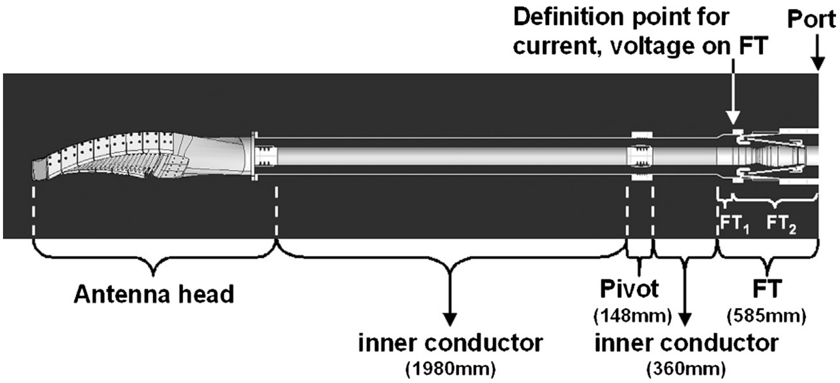

Fig. 1. Original HAS antenna.

2. Method of optimization of impedance transformer

Fig. 1 shows the original HAS antenna. The feed line between the antenna head and the ceramic feed-through is a simple coaxial line with the radii of 51 mm (outside of inner conductor) and 102 mm (inside of outer conductor). There is a ceramic feed-through (FT) and a pivot for the antenna drive on the line. To optimize the transformer between the antenna head and the ceramic feed-through, we must know the impedance of the antenna head for a typical plasma discharge. The impedance at the port can be measured with the directional coupler on the transmission line outside the vacuum vessel, and the head impedance is deduced with the impedance at the port and the scattering matrix of the line between the port and the antenna head simulated with HFSS (high frequency structure simulator, ANSYS). To optimize the transformer, the inner conductors are divided into several segments. The radius of the outer conductor is fixed to the original one, and the radii of inner conductors are given discretely and independently between the allowable minimum and maximum radii. The wave number k and the characteristic impedance Z_c in a segment are given as follows:

$$k = \frac{2\pi f}{c} - j\alpha \tag{1}$$

$$Z_c = Re(Z_c)\left(1 - j\frac{\alpha c}{2\pi f}\right) \tag{2}$$

where $\alpha = \frac{1}{2Re(Z_c)}\sqrt{\frac{f\mu}{\pi\sigma}}\left(\frac{1}{a}+\frac{1}{b}\right)$ (attenuation constant)

$$Re(Z_c) = \frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}}\ln\left(\frac{b}{a}\right)$$

f is the frequency and c is the light velocity. μ and σ are permeability and electric conductivity of the conductors, respectively. μ_0 and ε_0 are permeability and dielectric constant of vacuum, respectively. a and b are radii of inner and outer conductors, respectively. The reflection coefficient on the segment is calculated with the wave number, the characteristic impedance and the antenna side impedance Z_{ant} as follows:

$$\Gamma(x) = e^{-2jkx}\frac{Z_{\mathrm{ant}} - Z_c}{Z_{\mathrm{ant}} + Z_c} \tag{3}$$

where x is the distance from the end of antenna side. The voltage and the impedance on the point are formulated as follows:

$$V(x) = V_{\mathrm{ant}}\frac{1+\Gamma(x)}{e^{-jkx} + \Gamma(x)e^{jkx}} \tag{4}$$

$$Z(x) = Z_c\frac{1+\Gamma(x)}{1-\Gamma(x)} \tag{5}$$

where V_{ant} is the voltage at the end of antenna side. The electric field is the maximum on the inner conductor and determined as,

$$\left|E(x)\right| = \frac{\left|V(x)\right|}{a\ln(b/a)} \tag{6}$$

By using the voltage and impedance at the end of oscillator side, which are obtained by Eqs. (4) and (5), the voltage and impedance on the adjacent segment are calculated with the same procedure. However, in FT_1, FT_2 and the pivot shown in Fig. 1, this procedure cannot be used. Therefore simulated scattering matrixes of them are used to determine the adjacent voltage and impedance.

Here, we introduce a new concept, effective loading resistance:

$$R_{\mathrm{eff}} = \eta R \tag{7}$$

where η is the power transmission efficiency between port and antenna head, and R is the loading resistance at the port. Power to port is written as,

$$P_{\mathrm{port}} = \frac{1}{2}R\left(\frac{V_{\max}}{Z_{c0}}\right)^2 \tag{8}$$

where $V_{\max}$ and Z_{c0} are the maximum voltage and the characteristic impedance of the transmission line outside the vacuum vessel, respectively. Therefore the power to the antenna head is written as,

$$P_{\mathrm{head}} = \frac{1}{2}R_{\mathrm{eff}}\left(\frac{V_{\max}}{Z_{c0}}\right)^2 \tag{9}$$

This equation means that when the power to the head is fixed, lower voltage on the transmission line is possible with higher effective loading resistance.

We can obtain the maximum effective loading resistance by using all combinations of radii of inner conductors within the limitations of the voltage and current in the feed-through defined at the position indicated by the arrow in Fig. 1 and the electric field on the transformer. In our calculation electric field in transmission line is estimated with Eq. (6) at the three points i.e. the center and the both ends of segments. Around the obtained combinations of inner conductor radii, ranges of radii are narrowed and calculation is repeated several times for the precise optimization. Radii of the stepped transmission-line transformer are smoothed with three order polynomials. At the both ends of curves, slopes must be continuous to prevent the electric field from converging. Finally HFSS simulation is conducted to check the electric field since the convergence of electric field cannot be estimated with the above method, which is based on the assumption that the electric field is perpendicular to the axis of the transmission line.