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Pre-Stub Tuner for Reduction of Radio-Frequency Voltage Along Transmission Line in EAST-ICRF System

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Abstract — *The ion cyclotron range of frequency (ICRF) heating system of the Experimental Advanced Superconducting Tokamak (EAST) is characterized by high radio-frequency (RF) power up to 12 MW and wide frequency range over 25 to 70 MHz. A high RF power transmission system composed of a liquid impedance matching device, ceramic feedthrough, decoupler, and ICRF heating antenna with four straps has been in operation for some years. In a high-power ICRF experiment, one issue that needs to be solved is the high RF voltage on the coaxial transmission line between the ICRF antenna and the impedance matching device, which is caused by low antenna loading resistance compared to the characteristic impedance of the transmission line. A stub tuner is employed to reduce the RF voltage in the EAST ICRF power transmission system. Two methods to reduce RF voltage using short-circuited and open-circuited stub tuners are introduced in detail. The optimized position and length of the stub tuner are analyzed and calculated to achieve a smaller voltage reduction ratio (VRR) on the transmission line. The test with the stub tuner to reduce the RF voltage of the transmission line is carried out, and a RF VRR of ~0.57 is achieved. The RF voltage on the transmission line is significantly reduced, and the capability of the transmission power is obviously improved. Ohmic losses caused by the surface resistance of the conductor of the coaxial transmission line are also decreased, and the probability of breakdown within the transmission line is reduced under high RF power operation.*

Keywords — *Transmission line, RF voltage, EAST.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

As one of the primary auxiliary heating tools, an ion cyclotron range of frequency (ICRF) system is employed to provide radio-frequency (RF) energy to heat plasma inside a vacuum vessel via an impedance matching device and transmission line and ICRF antenna in a tokamak machine. The total RF power of the ICRF system for heating plasma has progressed from several megawatts to tens of megawatts in the major fusion devices in the world, and the ICRF system for ITER is required to deliver 20 MW of RF power to plasma.[1–4] Several power transmission lines are needed to deliver such high RF power, each of which must be capable of propagating no less than 1 MW of RF power consistently. In an experiment of ICRF high RF power heating, high RF voltage of the transmission line between the antenna and the impedance matching device will lead to breakdown inside the transmission line. In order to increase the standoff voltage and improve the performance of the RF power line, insulating gases pressurized with 0.3 to 0.5 MPa are commonly filled in the transmission line in many laboratories. High-voltage tests of the coaxial transmission line with different kinds of gases, such as CO_2, N_2, and SF_6, are carried out.[5,6] As a test result, carbon dioxide (CO_2) is normally chosen as a favorable gas because of its voltage tolerance and lack of toxicity and because it is nonpolluting.

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The Experimental Advanced Superconducting Tokamak (EAST) is a fully superconducting tokomak (R = 1.75 m, a = 0.4 m, and B_t = 3.5 T) at Institute of Plasma Physics, Chinese Academy of Sciences. Since the first plasma in 2006, great progress has been achieved.[7–9] An ICRF heating system with a total RF power of 12 MW and a frequency range of 25 to 70 MHz has been developed to support research on long-pulse high-β fusion physics experiments in EAST (Refs. 10 and 11), which includes eight RF power lines for plasma heating through two ICRF antennas at two ports: I and B. Each RF power line includes (a) a 1.5-MW transmitter consisting of a three-stage RF power amplifier chain and a high-voltage power supply set,[12–16] (b) an impedance matching device with a triple liquid stub tuner,[17,18] (c) a coaxial transmission line system including a direct-current (dc) break and decoupler network to suppress RF power cross between current straps of the antenna and a vacuum feedthrough to separate the vacuum vessel from air,[19,20] and (d) two antennas with four current straps the phases of which between straps can be controlled over a range of 0 to 360 deg at the low RF power part of the ICRF system.[21–23] Figure 1 is a block diagram of the four RF power lines of the ICRF heating system feeding antenna at B port on EAST.

In the ICRF heating experiment, one issue is the high RF voltage between the ICRF antenna and the impedance matching device caused by low antenna loading compared to the characteristic impedance of the transmission line of 50 Ω. The high RF voltage will lead to breakdown inside the transmission line under high RF power operation, especially in the situation of a high-voltage standing wave ratio (VSWR). Antenna loading resistance depends on the plasma parameter and the antenna condition, and it is normally <10 Ω. The antenna loading resistance R_A is defined as follows:

$$P_0 = \frac{R_A}{2} \cdot \frac{V_{max}^2}{Z_0^2}$$

and

$$P_0 = P_{for.} - P_{ref.} \ ,$$

where

P_0, $P_{for.}$, $P_{ref.}$ = injected RF power, forward RF power, and reflected RF power, respectively

Z_0 = characteristic impedance of transmission line

V_{max} = RF voltage maximum on the transmission line.

The maximal standing wave RF voltage will reach ~41 kV in the case of an injected RF power of 1 MW and antenna loading resistance of 3 Ω. The RF voltage will probably exceed the standoff voltage of the transmission line if the injected RF power is >1 MW or R is <3 Ω, and the risk of breakdown at the insulation spacer between the inner and outer conductors of the coaxial line will become too high.

In order to reduce the RF standing wave voltage and decrease the probability of breakdown within the transmission line, a stub tuner close to the ICRF antenna was installed and then was successfully tested to reduce the RF voltage in the EAST ICRF transmission line system. This paper is organized as follows. The ICRF transmission line system on EAST is introduced in Sec. II. In Sec. III, the optimized position and length of the short-circuited and open-circuited stub tuner to achieve a larger RF voltage drop on the transmission line are analyzed and calculated

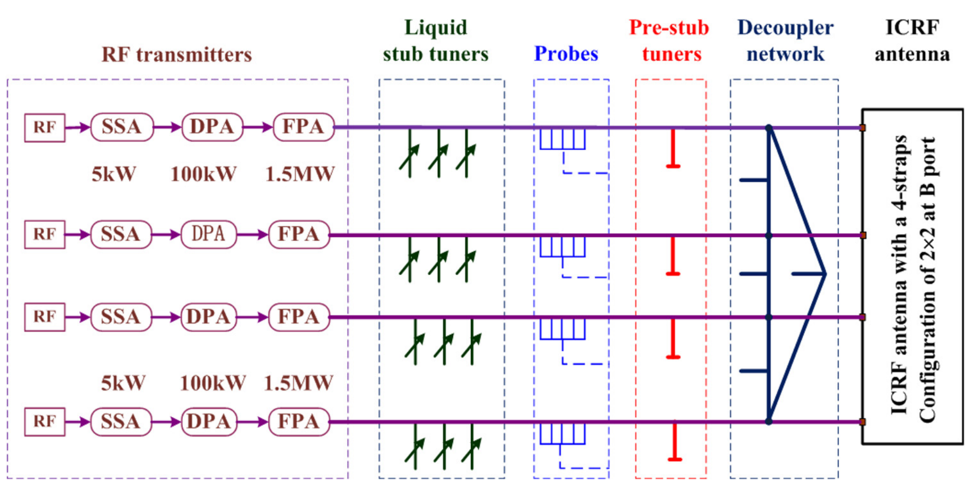

Fig. 1. Block diagram of the ICRF heating system feeding antenna at B port on EAST.

in detail. Section IV gives the tested results with the stub tuner, and finally Sec. V provides a summary.

II. ICRF TRANSMISSION LINE SYSTEM ON EAST

The ICRF transmission line system on EAST consists of eight sets of RF power lines and includes a RF power amplifier, dc break, impedance matching device, coaxial transmission line, decoupler network, vacuum feedthrough, and two ICRF antennas with four straps. In the EAST case, the coaxial transmission line with a characteristic impedance of 50 Ω is used, and the materials of the outer and inner conductors are aluminum and copper, respectively. Teflon insulation spacers are used in the coaxial line. The diameters of the outer and inner conductors are 230 and 100 mm, respectively. Dry nitrogen gas is pressurized at 0.3 MPa between the inner and outer conductors of the coaxial transmission line, and pure water with a pressure of 0.3 MPa is used for cooling the inner conductor. The standoff voltage of the coaxial transmission line is estimated to be ~40 kV. There are two ports (I port and B port) in EAST to be employed for ICRF antennas each to be designed with a different configuration, and each antenna has four current straps each fed by one separate RF power transmitter that is capable of launching a RF power of 1.5 MW. In order to overcome the mutual coupling effects between the current straps of the antenna, four decouplers are equipped for the antenna with a current strap configuration of 2 × 2 at B port, and five decouplers are used for the antenna with a current strap configuration of 1 × 4 at I port. The impedance matching device consists of three liquid stub tuners with a height of 7.41 m. The height of the liquid surface can be adjusted in the range from 0 to 7 m to change the input impedance of the liquid stub tuners. Silicon oil with a 2.2 dielectric constant is filled between the inner and outer conductors of the liquid stub tuner.

Normally, a short transmission line between the ICRF antenna and the impedance matching device is recommended due to the high VSWR, and the impedance matching device should be close to the tokamak machine to reduce the probability of breakdown. However, because the EAST housing does not have enough room for the impedance matching devices, eight sets of triple liquid stub tuners for impedance matching are placed far from the EAST machine, and the transmission line between the antenna and impedance matching device is ~80 m long. There are about 20 positions where the standing wave RF voltage is high, and breakdown probably occurs when the ICRF heating experiment is conducted at an operation frequency of 35 MHz in EAST.

On the other hand, a high VSWR caused by low ICRF antenna loading resistance will increase high ohmic RF losses on the transmission line that are proportional to the square of the standing wave RF voltage,[24] especially for the longer transmission line. For the low-loss coaxial transmission line, the attenuation constant of the coaxial transmission line can be expressed by the following equations[24]:

$$\alpha = \alpha_c + \alpha_d \ ,$$

$$\alpha_c = \frac{R_s}{4\pi Z_0}\left(\frac{1}{a} + \frac{1}{b}\right) \ ,$$

and

$$\alpha_d = \frac{\pi\sqrt{\varepsilon_r}}{\lambda}\tan\delta \ ,$$

where

α_c, α_d, δ = attenuation constant due to conductor loss, attenuation constant due to dielectric loss, and dielectric attenuation angle, respectively

a, b = radius of inner and outer conductors of coaxial line, respectively

R_s, Z_0 = surface resistance of conductor and characteristic impedance of coaxial line

ε_r = dielectric constant of medium

λ = wavelength of RF wave propagated in coaxial line.

The transmission efficiency of the coaxial line with a length of l can be determined as[24]

$$\eta = \frac{P_L}{P_{for.}} = \frac{1 - |\Gamma_L|^2}{e^{2\alpha l} - |\Gamma_L|^2 e^{-2\alpha l}} \ , \tag{1}$$

where P_L, $P_{for.}$, and Γ_L are the power delivered to the load, the forward power, and the reflection coefficient at the load, respectively.

In the EAST case, for the ICRF heating experiment, normally the antenna loading resistance is ~2.5 Ω, and the length of the transmission line is ~80 m, the overall thickness of the Teflon spacers is ~3 m, and the operation frequency is 35 MHz. Using the above-mentioned formulas, the transmission efficiency of the coaxial line is calculated to be ~88%. This is a low power propagation efficiency for the RF power transmission system. That means that the RF power dissipation on the transmission line due to conductor loss and medium loss will reach

~0.9 MW if the total RF power of 8 MW is launched by eight transmitters in the ICRF heating experiment on EAST. Furthermore, the standing wave RF voltage peak will reach ~45 kV, which exceeds the standoff voltage of the transmission line pressurized with 0.3 MPa of N_2 in the EAST case. But, if the antenna resistance is raised to a value of ~5 Ω (VSWR = 10), the power transmission efficiency of the coaxial line will rise to ~94%, and the standing wave RF voltage maximum of the transmission line will also decrease to ~31.6 kV. Therefore, besides reducing the length of the transmission line between the ICRF antenna and impedance matching device, it plays a key role for the EAST RF power transmission system to keep a low VSWR of the transmission line in order to reduce both the standing wave RF voltage and the RF power dissipation of the transmission line. Figure 2 shows the dependence of both the RF voltage maximum and the propagation efficiency of the transmission line on the antenna resistance.

III. DESIGN AND ANALYSIS OF TRANSMISSION LINE SYSTEM WITH PRE-STUB TUNER

III.A. Selection of Installation Position and Length of Stub Tuner

In order to reduce the RF voltage on the transmission line, a stub tuner (referred to as pre-stub tuner here) is installed in the transmission line near to the ICRF antenna. A key issue needed to be solved for the pre-stub tuner is to select the appropriate installation position and the length of the pre-stub tuner for a fixed ICRF antenna resistance. Assuming $y_1 = g_1 + jb_1$ is the input admittance of the transmission line at an arbitrary position normalized to the characteristic admittance of the transmission line, then two positions exist in the transmission line within one-half wavelength, where the real part of the normalized input admittance $g_1 = 1$. If a short-circuit stub tuner or open-circuit stub tuner with an input admittance $y_2 = jb_2$ is installed at the position of $g_1 = 1$, and when $b_2 = -b_1$ is made, the overall input admittance of the transmission line including the pre-stub tuner at the position of $g_1 = 1$ can be written as

$$y_{in} = y_1 + y_2 = g_1 + jb_1 + jb_2 = 1 \quad . \tag{2}$$

This means that the imaginary part of input admittance y_1 of the transmission line is eliminated due to the connection of the pre-stub tuner and the input impedance of the transmission line with the pre-stub tuner at the position of $g_1 = 1$ is equal to the characteristic impedance of the transmission line.

For the pre-stub tuner with an equivalent electrical length less than one-quarter wavelength, it is terminated either in a short circuit, $Z_L = 0$, or in an open circuit, $Z_L = \infty$; this depends on the property of the input impedance of the transmission line at the position of the pre-stub tuner. The short-circuit pre-stub tuner should be installed at the position where the imaginary part of the input impedance is capacitive, and the open-circuit one should be located at the position where the imaginary part of the input impedance is inductive. The installation position of the pre-stub tuner corresponding to the standing wave RF voltage distribution along the transmission line is illustrated with arrows in Fig. 3.

For a fixed antenna impedance Z_A, the normalized input admittance y_1 of the transmission line can be written as

$$y_1 = \frac{Y_A + jY_0 \tan(2\pi A_{AL})}{Y_0 + jY_A \tan(2\pi A_{AL})} = g_1 + jb_1 \tag{3}$$

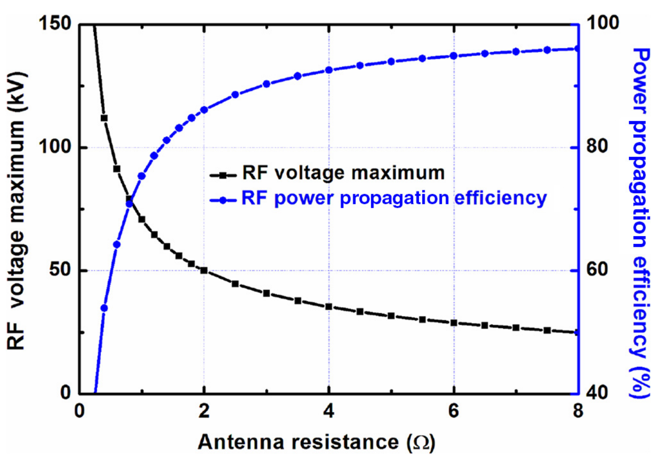

Fig. 2. Dependence of both RF voltage maximum and RF power propagation efficiency on the antenna resistance under the condition of injected RF power P = 1 MW, working frequency f = 35 MHz, length of transmission line L = 80 m, and thickness of overall insulated Teflon spacers T = 3 m.

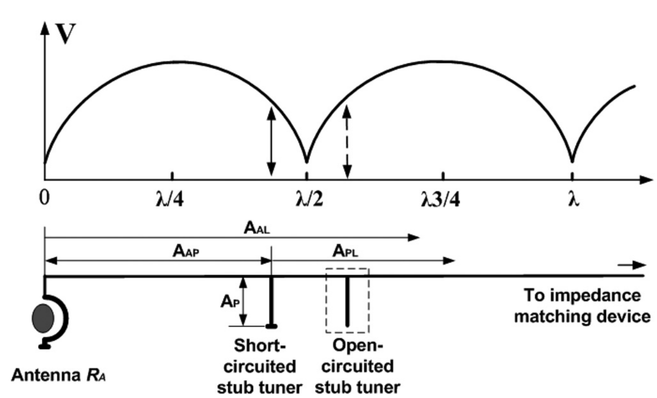

Fig. 3. Installation position of the pre-stub tuner corresponding to standing wave RF voltage distribution along transmission line.

and

$$g_1 = \frac{Y_0 Y_A (1 + \tan^2(2\pi A_{AL}))}{Y_0^2 + Y_A^2 \tan^2(2\pi A_{AL})}$$

$$b_1 = \frac{(Y_0^2 - Y_A^2)\tan(2\pi A_{AL})}{Y_0^2 + Y_A^2 \tan^2(2\pi A_{AL})} , \quad (4)$$

where

Y_0 = characteristic admittance of transmission line

Y_A = antenna admittance

A_{AL} = length of transmission line from ICRF antenna to an arbitrary position L of transmission line normalized with RF wavelength

g_1, b_1 = real part and imaginary part of normalized input admittance, respectively.

The optimum normalized position A_{AL} of the pre-stub tuner can be calculated using Eq. (5) when making $g_1 = 1$:

$$\tan(2\pi A_{AL}) = \pm\left(\frac{Y_0}{Y_A}\right)^{1/2} . \quad (5)$$

There are two solutions for Eq. (5), which are respectively corresponding to the two best positions of the pre-stub tuner. One is for the short-circuit stub tuner, and another is for the open-circuit stub tuner. The imaginary part of the input admittance at the best position will be completely eliminated by the input admittance of the pre-stub tuner, so the best normalized length A_P of the pre-stub tuner can be calculated using Eq. (6):

$$y_2 = -j\frac{1}{\tan(2\pi A_P)} = -jb_1 . \quad (6)$$

III.B. Radio-Frequency Voltage Distribution with Short-Circuit Stub Tuner Along Transmission Line

Assuming that the antenna resistance is R_A and that the length of the transmission line from the ICRF antenna to an arbitrary position L in the transmission line normalized to the RF wavelength is A_{AL}, the RF voltage V_L and RF current I_L can be expressed by Eq. (7):

$$\begin{pmatrix} V_L \\ I_L \end{pmatrix} = \begin{pmatrix} \cos(2\pi A_{AL}) & jZ_0 \sin(2\pi A_{AL}) \\ j/Z_0 \sin(2\pi A_{AL}) & \cos(2\pi A_{AL}) \end{pmatrix} \begin{pmatrix} V_A \\ I_A \end{pmatrix} , \quad (7)$$

where V_A and I_A are the RF voltage and the RF current at the antenna, respectively. Then,

$$V_L = V_A \cos(2\pi A_{AL}) + jZ_0 I_A \sin(2\pi A_{AL})$$

and

$$I_L = I_A \cos(2\pi A_{AL}) + jV_A/Z_0 \sin(2\pi A_{AL}) . \quad (8)$$

At the antenna, $A_{AL} = 0$, $V_L = V_A$, and $I_L = I_A$; then, the resistance R_A at the antenna is expressed using V_A and I_A:

$$R_A = \frac{V_A}{I_A} .$$

So, the RF voltage V_L and the RF current I_L at an arbitrary position L are given by Eqs. (9):

$$V_L = V_A(\cos(2\pi A_{AL}) + jZ_0/R_A \sin(2\pi A_{AL}))$$

and

$$I_L = V_A(1/R_A(\cos(2\pi A_{AL}) + j1/Z_0 \sin(2\pi A_{AL})) . \quad (9)$$

The magnitude of the RF voltage V_L normalized to the antenna RF voltage V_A is

$$\left|\frac{V_L}{V_A}\right| = \left(\cos^2(2\pi A_{AL}) + \left(\frac{Z_0}{R_A}\right)^2 \sin^2(2\pi A_{AL})\right)^{1/2} . \quad (10)$$

At the installation position P of the pre-stub tuner, $A_{AL} = A_{AP}$; then, the RF voltage V_P and the RF current I_P at the position of the pre-stub tuner are expressed using Eqs. (11):

$$V_P = V_A(\cos(2\pi A_{AP}) + jZ_0/R_A \sin(2\pi A_{AP}))$$

and

$$I_P = V_A(1/R_A(\cos(2\pi A_{AP}) + j1/Z_0 \sin(2\pi A_{AP})) . \quad (11)$$

Assuming that the antenna resistance $R_A = 2\ \Omega$ and the characteristic impedance of coaxial line $Z_0 = 50\ \Omega$ are employed, the RF voltage distribution along the coaxial transmission line is calculated using Eq. (10) as shown in Fig. 4. In this case, VSWR = 25; that is, $V_{MAX}/V_A = 25$.

When a pre-stub tuner is installed between the ICRF antenna and the impedance matching device, the standing wave RF voltage of the transmission line between the pre-stub tuner and the impedance matching device can be reduced significantly by choosing the optimized position A_{AP} and length A_P of the pre-stub tuner. For the short-circuit stub tuner, the RF voltage V_L and the RF current I_L at an arbitrary position L of the transmission line between the pre-stub tuner and the impedance matching device are expressed by Eq. (12):

$$\begin{aligned}\begin{pmatrix}V_L\\ I_L\end{pmatrix} &= \begin{pmatrix}\cos(2\pi A_{PL}) & jZ_0\sin(2\pi A_{PL})\\ j/Z_0\sin(2\pi A_{PL}) & \cos(2\pi A_{PL})\end{pmatrix}\begin{pmatrix}1 & 0\\ -j/Z_0/\tan(2\pi A_P) & 1\end{pmatrix}\begin{pmatrix}V_P\\ I_P\end{pmatrix}\\ &= \begin{pmatrix}\cos(2\pi A_{PL}) & jZ_0\sin(2\pi A_{PL})\\ j/Z_0\sin(2\pi A_{PL}) & \cos(2\pi A_{PL})\end{pmatrix}\begin{pmatrix}V_P\\ I_P - jV_P/Z_0/\tan(2\pi A_P)\end{pmatrix}\\ &= \begin{pmatrix}V_P\cos(2\pi A_{PL}) & V_P\sin(2\pi A_{PL})/\tan(2\pi A_P) + jZ_0 I_P\sin(2\pi A_{PL})\\ jV_P/Z_0\sin(2\pi A_{PL}) & \cos(2\pi A_{PL})(I_P - jV_P/Z_0/\tan(2\pi A_P))\end{pmatrix} . \end{aligned} \quad (12)$$

Then, RF voltage V_L at position L is written by

$$V_L = V_P\left[\cos(2\pi A_{PL}) + \frac{\sin(2\pi A_{PL})}{\tan(2\pi A_P)}\right] + jZ_0 I_P\sin(2\pi A_{PL}) , \quad (13)$$

where A_{PL} is the normalized distance from the pre-stub tuner to an arbitrary position L of the transmission line between the pre-stub tuner and impedance matching device and A_P is the normalized length of the pre-stub tuner. Substituting Eqs. (11) into the Eq. (13), the RF voltage V_L normalized to the antenna RF voltage V_A can be expressed using the following complex formula:

$$\begin{aligned}\frac{V_L}{V_A} &= \left\{\cos(2\pi A_{AP})\left(\cos(2\pi A_{PL}) + \frac{\sin(2\pi A_{PL})}{\tan(2\pi A_P)}\right) - \sin(2\pi A_{AP})\sin(2\pi A_{PL})\right\}\\ &+ j\frac{Z_0}{R_A}\left\{\sin(2\pi A_{AP})\left(\cos(2\pi A_{PL}) + \frac{\sin(2\pi A_{PL})}{\tan(2\pi A_P)}\right) + \cos(2\pi A_{AP})\sin(2\pi A_{PL})\right\} .\end{aligned} \quad (14)$$

And, the absolute value of the normalized RF voltage V_L/V_A is

$$\left|\frac{V_L}{V_A}\right| = \left(V_{real}^2 + V_{imag}^2\right)^{1/2} , \quad (15)$$

where V_{real} and V_{imag} are the real part and the imaginary part of the normalized RF voltage V_L/V_A. The RF voltage distribution with the pre-stub tuner along the transmission line can be computed by using Eqs. (10) and (15), and the reduction ratio of the RF voltage with the pre-stub tuner to the RF voltage without the pre-stub tuner can be also obtained.

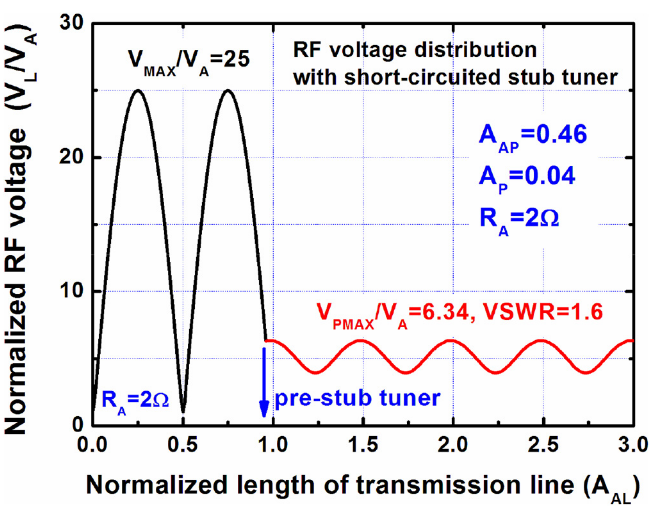

Fig. 4. Radio-frequency voltage distribution with short-circuit pre-stub tuner along transmission line when keeping $A_P + A_{AP} = 0.5$.

The calculated RF voltage distribution with the short-circuited pre-stub tuner along the transmission line for an antenna resistance of $R_A = 2\ \Omega$ is shown in Figs. 4, 5, and 6. The pre-stub tuner is located at $A_{AP} = 0.46$ (here A_{AP} is the equivalent electric length, and the normalized length is $0.5 \times 2 + A_{AP} = 1.46$ as indicated by the blue arrows in Figs. 4, 5, and 6), and the normalized lengths A_P of the pre-stub tuner are 0.04, 0.08, and 0.03, respectively. In Fig. 4, the normalized RF voltage maximum of the transmission line between the pre-stub tuner and the impedance matching device is significantly reduced from $V_{MAX}/V_A = 25$ to $V_{PMAX}/V_A = 6.3$, and the VSWR with the pre-stub tuner is decreased from 25 to 1.6. However, it is found that the VSWR of the transmission line with $A_P = 0.08$ and 0.03 is higher than that with $A_P = 0.04$ when comparing Fig. 4 with Figs. 5 and 6. The reason is that the best condition of $A_P + A_{AP} = 0.5$ is selected in Fig. 4. This means that the smaller reduction ratio V_{PMAX}/V_{MAX} of the RF voltage would be obtained when the overall length of the pre-stub tuner plus the transmission line between the antenna and the pre-stub tuner is the integer multiple of the one-half wavelength for the short-circuit pre-stub

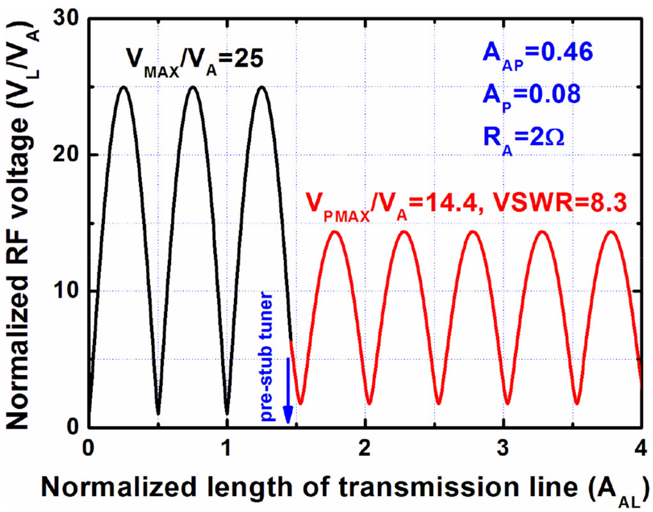

Fig. 5. Radio-frequency voltage distribution with short-circuit pre-stub tuner along transmission line in the case of $A_P = 0.08$ and $A_P + A_{AP} \neq 0.5$.

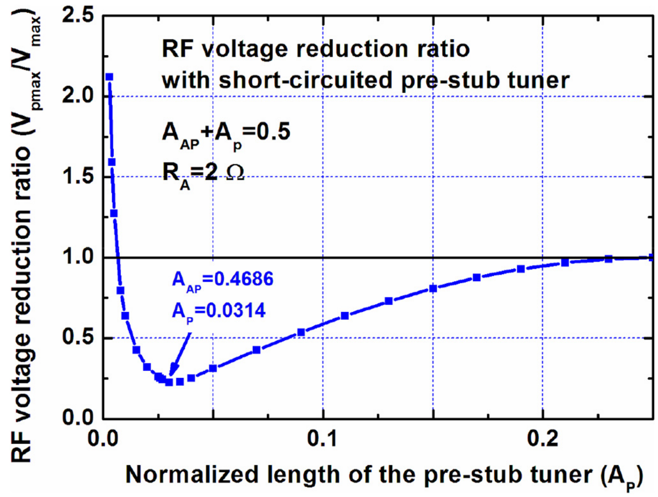

Fig. 7. Radio-frequency VRR with the length of short-circuit pre-stub tuner when keeping $A_P + A_{AP} = 0.5$ and antenna resistance $R_A = 2\ \Omega$.

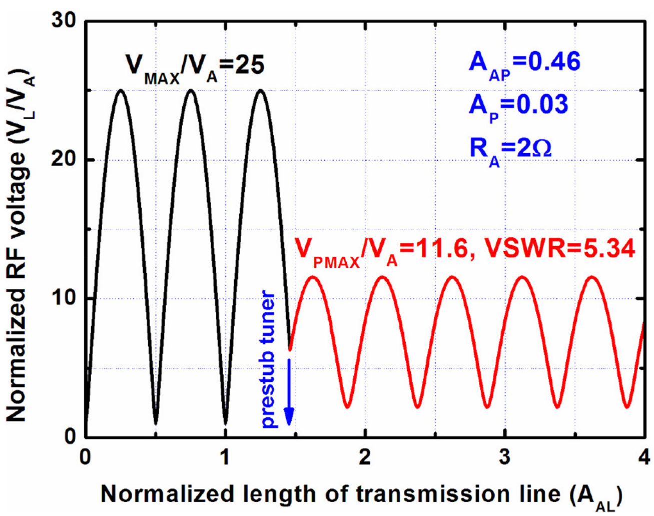

Fig. 6. Radio-frequency voltage distribution with short-circuit pre-stub tuner along transmission line in the case of $A_P = 0.03$ and $A_P + A_{AP} \neq 0.5$.

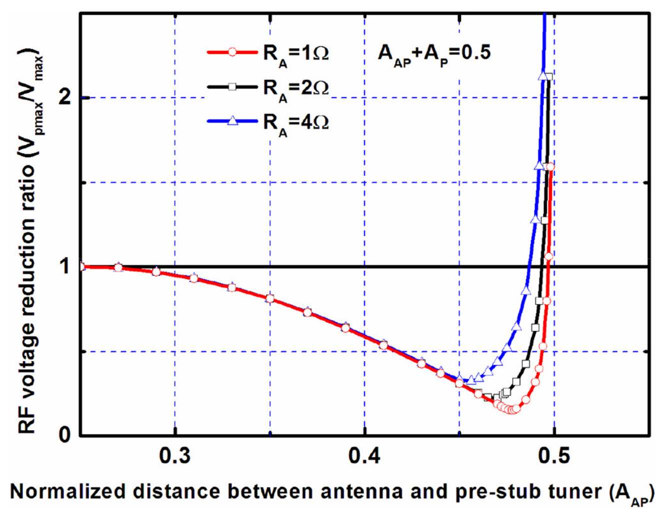

Fig. 8. Radio-frequency VRR with the length of short-circuited stub tuner for the different antenna resistance when keeping $A_P + A_{AP} = 0.5$.

tuner. Here, we define VRR as the ratio of the RF voltage maximum with the pre-stub tuner V_{PMAX} divided by the RF voltage maximum without the pre-stub tuner V_{MAX} in the transmission line, that is, VRR $= V_{PMAX}/V_{MAX}$.

As usual, the shorter the pre-stub tuner is, the smaller the RF VRR V_{PMAX}/V_{MAX} will be when keeping $A_P + A_{AP} = 0.5$. At the best position of the pre-stub tuner of $A_{AP} = 0.4686$ and $A_P = 0.0314$, the input impedance with the pre-stub tuner is approximately equal to the characteristic impedance of the transmission line for an antenna resistance of $R_A = 2\ \Omega$. However, the RF VRR will increase sharply once the length of the pre-stub tuner is less than the best length of A_P or the value of A_{AP} is more than the best position as shown in Figs. 7 and 8. It can also be found in Fig. 7 that the RF VRR is almost the same when the antenna resistance changes from 1 to 4 Ω under the condition of $A_{AP} + A_P = 0.5$ in spite of A_{AP} changing from 0.25 to 0.42, but the best position of the pre-stub tuner is shifted toward the ICRF antenna. Usually, the larger the antenna loading resistance is, the shorter the distance from the ICRF antenna to the pre-stub tuner will be, and the longer the length of the pre-stub tuner will be.

In the ICRF heating experiment, plasma instability will cause a great change in antenna resistance due to strong coupling between the ICRF antenna and plasmas, especially for transients from L-mode to H-mode or edge-localized modes, so there is a risk whereby the RF voltage rises steeply when A_{AP} is more than the optimum value or A_P is less than the optimum value. In addition, errors of engineering and calculation need to be taken into account. The pre-stub tuner should be designed to achieve high tolerance to such errors. Therefore, the safe selection for practical application is that A_{AP} should be a little less than the optimum value and A_P should be a little more than the optimum value when keeping $A_{AP} + A_P = 0.5$ in order to avoid those positions of the pre-stub tuner where the RF voltage steeply rises.

For a fixed antenna resistance R_A, the RF voltage drop with the pre-stub tuner is dependent on the combination of A_{AP} and A_P. But, sometimes, inappropriate combinations of A_{AP} and A_P will result in a higher VSWR than that without a pre-stub tuner. So, it is essential to find the safe matching combination of A_{AP} and A_P.

The normalized input admittance including the pre-stub tuner at the position of the pre-stub tuner can be written by Eq. (16) using Eqs. (2) and (6):

$$y_{in} = y_1 + y_2 = g_1 + jb_1 - j1/\tan(2\pi A_P) \quad . \tag{16}$$

The voltage reflection coefficient Γ_P with the pre-stub tuner at the position of the pre-stub tuner is expressed as

$$\Gamma_P = \frac{1 - y_{in}}{1 + y_{in}} \quad . \tag{17}$$

Substituting formula (16) into formula (17), formula (18) can be derived:

$$\frac{1}{\tan(2\pi A_P)} = b_1 \pm \left\{ \frac{4g_1}{1 - |\Gamma_P|^2} - (1 + g_1)^2 \right\}^{1/2} \quad . \tag{18}$$

Figure 9 is a contour map of the voltage reflection coefficient on the A_P-A_{AP} plane calculated using formula (18) in the case of antenna resistance of 2 Ω. In this map, the line of reflection coefficient with the value of 0.92 corresponds to a RF VRR of 1, where the pre-stub tuner has no effect and there is no RF voltage drop or rise; the other lines represent the RF VRR of <1. It is a convenient way to find the better matching combination of A_P and A_{AP} utilizing this contour map even if the sum of A_P and A_{AP} is not equal to 0.5 in order to achieve the large RF voltage drop.

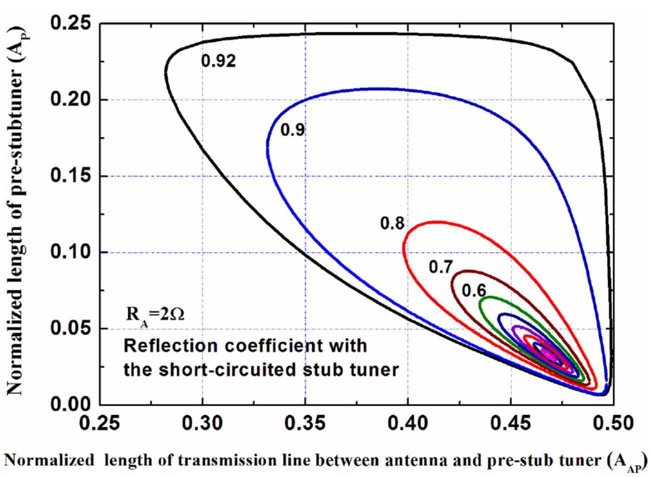

Fig. 9. Contour map of the voltage reflection coefficient on A_P-A_{AP} plane in the case of antenna resistance $R_A = 2$ Ω.

III.C. Radio-Frequency Voltage Distribution Along Transmission Line with Open-Circuit Stub Tuner

The RF standing wave voltage can also be reduced by selecting the optimum position and length of an open-circuit stub tuner with a length less than one-quarter wavelength. The analysis and calculation methods are similar to those with the short-circuit stub tuner as described in Sec. III.B. Actually, an open-circuited stub tuner can be transformed into an equivalent short-circuited stub tuner by adding the length of a one-quarter wavelength, which is equivalent to the other solution of the short-circuited stub that has a physical length between one-quarter and one-half wavelength. To replace the parameters of the short-circuit stub tuner with ones of an open-circuit stub tuner in formula (12) or elongate the short-circuit stub tuner to a range of 1/4 λ ~ 1/2 λ, the RF voltage V_L normalized to the antenna voltage V_A with the open-circuit stub tuner can be derived as follows:

$$\begin{aligned}\frac{V_L}{V_A} &= \{\cos(2\pi A_{AP})(\cos(2\pi A_{PL}) - \sin(2\pi A_{PL})\tan(2\pi A_P)) \\ &\quad - \sin(2\pi A_{AP})\sin(2\pi A_{PL})\} + j\frac{Z_0}{R_A}\{\sin(2\pi A_{AP}) \\ &\quad \times (\cos(2\pi A_{PL}) - \sin(2\pi A_{PL})\tan(2\pi A_P)) \\ &\quad + \cos(2\pi A_{AP})\sin(2\pi A_{PL})\} \quad .\end{aligned} \tag{19}$$

Then, the absolute value of the normalized RF voltage V_L/V_A can be calculated using this complex formula in the same method as mentioned above.

Because the input admittance of the open-circuit stub tuner with a length less than one-quarter wavelength is capacitive, the input admittance of the transmission line at the position of the open-circuit pre-stub tuner should be conductive, which is opposite of the characteristics compared with that at the position of the short-circuit pre-stub tuner. The best condition for the open-circuit pre-stub tuner is $A_{AP} + A_P = 0.25$, which is different from that with the short-circuit pre-stub tuner. When employing $R_A = 2$ Ω and $Z_0 = 50$ Ω, the RF voltage distribution with the open-circuit pre-stub tuner is shown in Fig. 10. The open-circuit pre-stub tuner is located at $A_{AP} = 0.05$ (the normalized

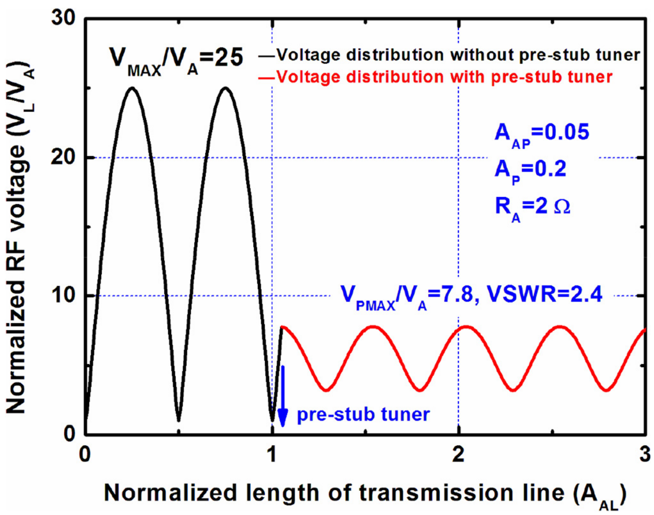

Fig. 10. Radio-frequency voltage distribution with open-circuit stub tuner along transmission line with $A_{AP} = 0.05$ and $A_P = 0.2$.

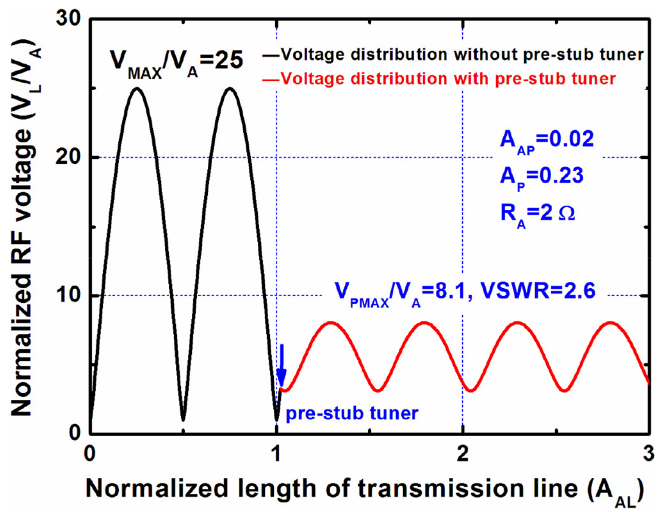

Fig. 11. Radio-frequency voltage distribution with open-circuit stub tuner along transmission line with $A_{AP} = 0.02$ and $A_P = 0.23$.

position of the pre-stub tuner is $1.25 = 0.5 \times 2 + A_{AP}$ as indicated by the blue arrow in Fig. 10).

Generally, the optimum position of the open-circuit pre-stub tuner is $A_{AP} + A_P = 0.25 + 0.5 \times n$, where the RF voltage is approximately equal to the node voltage or the antinode voltage on the transmission line between the pre-stub tuner and the impedance matching device as shown in Figs. 10 and 11, respectively. Figure 12 shows dependence of the RF VRR on the normalized length of the open-circuit pre-stub tuner when keeping $A_{AP} + A_P = 0.25$. The best combination of A_{AP} and A_P is $A_{AP} = 0.0314$ and $A_P = 0.2186$ for an antenna resistance $R_A = 2\ \Omega$ as indicated by the red arrow in Fig. 12. In this case, the RF VRR will reach 0.22. In addition, it can be also found that RF VRR will rapidly rise once the normalized length of the pre-stub tuner is more than the best value of $A_P = 0.2186$. This is similar to the case with the short-circuit pre-stub tuner.

Figure 13 is the computed contour map of the RF VRR on the A_P-A_{AP} plane in the case of antenna resistance of 2 Ω. In order to obtain a large RF voltage reduction with the open-circuit pre-stub tuner, a better combination of A_{AP} and A_P can be found under the condition of $A_{AP} + A_P \neq 0.25$ utilizing this map.

III.D. Consideration for the Impedance Matching Device with Triple Stub Tuner

The impedance matching device for ICRF heating on EAST consists of three liquid stub tuners, and silicon oil with a dielectric constant of 2.2 is filled between the inner and outer conductors of the stub tuner. To reduce the probability of breakdown within the liquid stub tuners, it

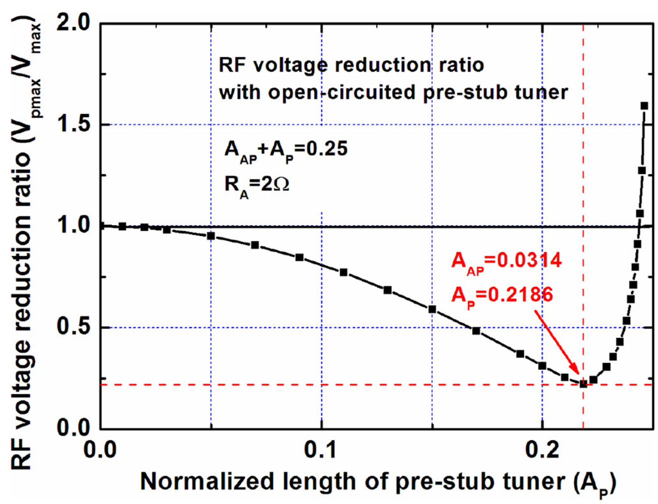

Fig. 12. Dependence of RF VRR on the normalized length of the open-circuit stub tuner when keeping $A_{AP} + A_P = 0.25$ and antenna resistance $R_A = 2\ \Omega$.

is important to choose a suitable position of the liquid stub tuner in the antenna side, which depends on the input impedance of the transmission line at the position of the liquid stub tuner in the antenna side. An inappropriate position will result in a large rise in RF voltage of the liquid stub tuners. For the impedance matching device with a stub tuner, if the input impedance of the transmission line at the position of the liquid stub tuner in the antenna side (not including the liquid stub tuner) is capacitive, the input impedance of the liquid stub tuner in the antenna side should be inductive, and vice versa. In the EAST case, the liquid stub tuner for impedance matching is 7.4 m in height, and its input impedance is varied with the height of the liquid surface from 0 to 7 m. There are

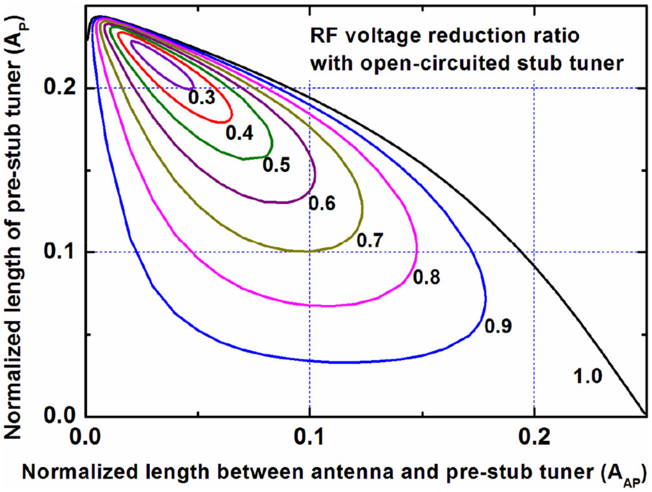

Fig. 13. Calculated contour map of the RF VRR on A_{AP}-A_P plane for the antenna resistance $R_A = 2\ \Omega$.

two ways to avoid the rise in RF voltage by making the input impedance characteristics of the liquid stub tuner contrary to that of the transmission line at the position of the liquid stub tuner in the antenna side: (a) to adjust the liquid surface height of the liquid stub tuner in the antenna side and (b) to adjust the length of the transmission line between the pre-stub tuner and the impedance matching device by using a trombone coaxial line.

IV. EXPERIMENTAL TEST AND DISCUSSION

For the best combination of A_{AP} and A_P, the input impedance at the position of the pre-stub tuner should be near to the characteristic impedance of the transmission line, and the RF voltage distribution along the transmission line between the pre-stub tuner and the impedance matching device should be performed with an approximate traveling wave state. However, it is a little difficult to measure the exact value of the RF antenna resistance in the ICRF heating experiment due to plasma instability. Therefore, it is still a better selection for A_{AP} and A_P even if $A_{AP} + A_P \neq 0.5$ (for the short-circuited stub tuner) or $A_{AP} + A_P \neq 0.25$ (for the open-circuited stub tuner) as long as the large RF voltage drop can be achieved.

The test for the RF voltage reduction with the short-circuited pre-stub tuner was conducted at a frequency of 35 MHz on EAST. The pre-stub tuners closest to the ICRF antenna were installed in the coaxial line feeding the antenna with a current strap configuration of 2 × 2 at B port. The RF voltage distribution without the pre-stub tuner was measured by means of voltage probes mounted in the transmission line. The antenna resistance with plasma is estimated to be ~2.5 Ω, and the positions of the pre-stub tuner were determined to be $A_P = 0.036$ and $A_{AP} = 0.462$, which have a small offset of $\Delta A_P = -0.001$ and $\Delta A_{AP} = 0.003$ from the best position of the pre-stub tuner. The test result of one of the power lines is shown in Fig. 14. The RF power injected is 180 kW in this test. The RF voltage peak is reduced from ~18.9 to ~10.7 kV, and VSWR is reduced from ~20 to ~6.5. This means that the equivalent loading resistance of the ICRF antenna is increased to ~7.9 Ω. The standing wave RF voltage with the pre-stub tuner is greatly reduced. The lower probability of high-voltage breakdown can be expected under high-power operation for the ICRF RF power transmission system. Obviously, the transmission losses of RF power are also greatly reduced due to a drop in VSWR after installation of the pre-stub tuner. Figure 15 shows the reduction of the transmission line loss due to the decrease of VSWR in the test.

Because the antenna's resistance depends on the plasma conditions and antenna loading and the length and location of the pre-stub tuner are sensitive to the plasma loading, high tolerance to changes in antenna resistance for the engineering design of the pre-stub tuner is needed to achieve a low VRR after the pre-stub tuner is installed. As usual, the plasma density n_{e0} is 2×10^{-19} to 3×10^{-19}, the gap between the limiter and the last closed flux surface is ~3 cm, the plasma current I_P is ~500 kA, and the toroidal magnetic field B_t is ~2.3 T for the ICRF experiment in EAST. The antenna resistance changes in the range from 2.0 to 3.2 Ω according to the plasma density as shown in Fig. 16. A median value of antenna resistance of 2.5 Ω was chosen for the design of the pre-stub tuner. This is a compromise to the unstable antenna coupling impedance. In the EAST case, this is generally satisfactory

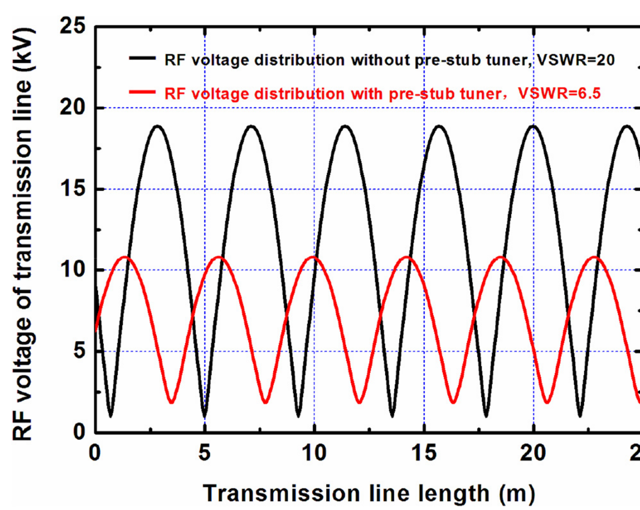

Fig. 14. Tested RF voltage distribution along transmission line with and without the short-circuited pre-stub tuner for an injection RF power of 180 kW at 35 MHz.

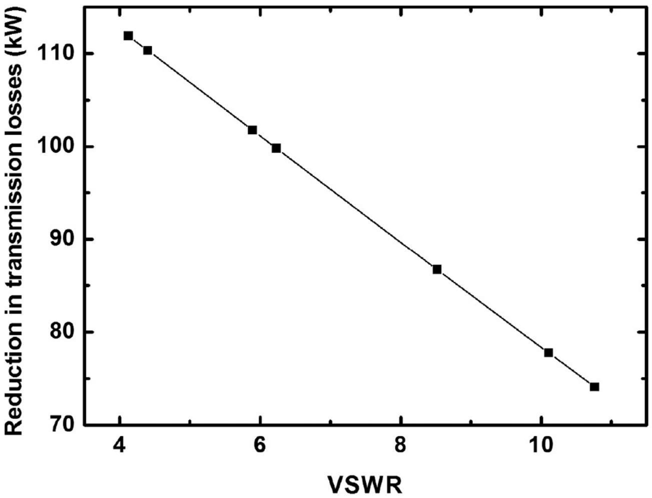

Fig. 15. Reduction in transmission line loss with the pre-stub tuner versus VSWR under the conditions of RF power of 1 MW, operation frequency of 35 MHz, transmission line length of 80 m, and thickness of 3 m of total insulated Teflon spacers.

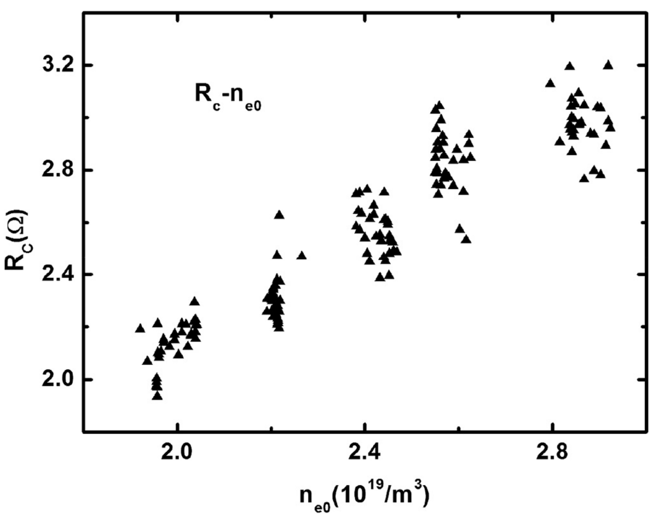

Fig. 16. Variation in the antenna resistance with electron density under the following conditions: The gap between limiter and last closed flux surface is ~3 cm, the plasma current is ~500 kA, and the toroidal magnetic field is ~2.3 T.

under a range of different plasma conditions for the ICRF experiment at present.

However, the measured RF voltage reduction ratio V_{PMAX}/V_{MAX} is a little higher than the calculated results although a large RF voltage reduction is achieved compared to the case without the pre-stub tuner. For an antenna resistance of 2.5 Ω, the calculated V_{PMAX}/V_{MAX} is ~0.28 in the case of the positions of the pre-stub tuner $A_P = 0.036$ and $A_{AP} = 0.46$, but the measured V_{PMAX}/V_{MAX} is 0.57 in the test. Such a larger RF VRR in engineering application results from the following factors: (a) overcorrection on the position and length of the pre-stub tuner; (b) unstable antenna resistance due to different plasma conditions and antenna loading; (c) variation in the characteristic impedance of the transmission line caused by elbows and T-junctions and insulated spacers, etc.; and (d) real value of the antenna resistance being a little more than or less than 2.5 Ω.

Even though the amendment in position and length of the pre-stub tuner was made based on the calculated results, the theoretical results still do not agree well with the experimental data. The reason is that the calculation was carried out using ideal transmission line equations. Therefore, there is considerable room for further improvement in the engineering design of the pre-stub tuner system in order to achieve a lower RF VRR in the future.

V. CONCLUSION

Based on transmission line theory, a pre-stub tuner with different properties to reduce RF standing wave voltage on a transmission line was chosen based on the input impedance of the transmission line at the position of the pre-stub tuner. The RF voltage distributions along the transmission line with short-circuited and open-circuited pre-stub tuners were calculated in detail, and the optimized position of the pre-stub tuner was determined for the fixed antenna resistance. The short-circuited pre-stub tuner nearest to the ICRF antenna was installed in the EAST ICRF transmission line feeding the four-strap antenna at port B. A RF voltage reduction test was successfully carried out at a frequency of 35 MHz. The test results show that RF voltage was greatly reduced compared to that without the pre-stub tuner, and a RF VRR of ~0.57 was achieved. The probability of breakdown was decreased, and reliability was improved for the ICRF high RF power transmission system on EAST. The RF power delivery under low RF ohmic loss with the pre-stub tuner is possible because of the smaller VSWR of the transmission line between the pre-stub tuner and the impedance matching device, and higher RF power propagation efficiency can be expected.

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