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ICRF antenna impedance measurements with voltage and current probes on EAST

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ABSTRACT

A new set of measurement system on the Experimental Advanced Superconducting Tokamak (EAST), based on voltage and current probes, is installed on transmission line between matching system and ion cyclotron range of frequencies antenna to measure the antenna input impedance. The data can be used for impedance-matching points optimizing, as well as coupling coefficient assessment by deducing the antenna coupling resistance from antenna input impedance. The measurement error of amplitude and phase difference show distinct impact on the coupling resistance. Generally, the amplitude measurement error has a small impact on coupling resistance, while the phase measurement error significantly affects the coupling resistance. Instead of using phase detectors, phases can be extract from the power measurements. Thus, the antenna input impedance and coupling resistance can be deduced from the amplitude of voltage probe, amplitude of current probe, as well as the antenna feeding power. on previous experiments, the impedance measurement technique based on voltage probes array is utilized to evaluate coupling resistances. In EAST 2016 campaign, the load coupling resistance calculated by using such two techniques were detected and the results showed agreement.

1. Introduction

The Advanced Experiment Superconductive Tokamak (EAST) is designed for long-pulse divertor operations [1]. Ion Cyclotron Range of Frequency (ICRF) is one of the main auxiliary heating tools on EAST for its mature operation, low economic cost, and the ability to heat ions that is crucial for achieving high confinement mode (H-mode) steady state plasmas [2]. High level of radio frequency (RF) power are launched through 8 coaxial transmission lines, and are coupled to the plasma through two antennas. One antenna located at B-port is composed of an array of 2 toroidal by 2 poloidal current straps, the other one at I-port is composed of an array of 4 straps aligned on the toroidal direction [3]. An impedance-matching device named liquid three-stub tuner enables to match the antenna load with the characteristic impedance of transmission line [4]. The decoupler installed between two transmission lines is used to balance the RF power between adjacent current straps and suppress mutual influence of RF power induced by coupling between them [5].

During EAST 2012 campaign, voltage probes (V probe) were installed to measure the standing voltage distribution along transmission line. In 2015, the voltage and current probe (I probe) pairs (V/I probes pair) were used to measure the ICRF antenna impedance by measuring the amplitude of transmission line voltage, current as well as phase difference between voltage and current. The antenna input impedance and the coupling resistance can be written as: $Z_L = \frac{|U|}{|I|}e^{j\varphi}$, $\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0}$, $R_L = Z_0\frac{1-|\Gamma_L|}{1+|\Gamma_L|}$. In the formulas, Z_L, Γ_L, R_L, Z_0 are the antenna input impedance, complex reflection coefficient, coupling resistance, and the characteristic impedance of transmission line, respectively. Based on phase detector, the bad precision of phase measurement sometimes leads to the fail of the impedance calculation. While calculation technique based on power, amplitude of voltage and current provides logical results. The power is measured by directional couplers near the transmitter, where a relatively low Voltage Standing Wave Ratio (VSWR) is guaranteed, at a high VSWR the directional couplers fail because of their limited directivity [6]. To evaluate the feeding power,

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power loss should be considered because of the long distance and high VSWR between matching devices and the antenna.

In Section 2 of this paper, ICRF system and the impedance measurement components are introduced. In section 3, the electrical circuits of V/I probes are described, the issues above the probes calibration are introduced and calibration results are compared with simulation ones. In Section 4, the impact of phase measurement error on impedance is addressed, arithmetic of calculation applying power is introduced, and the impact of power loss error is analyzed. The measurement results of antenna coupling resistance are given in Section 5.

2. Impedance measurement system in EAST-ICRF

The ICRF system on EAST consists of 8 transmission networks. RF power (34 MHz for power lines 1–4 and 35 MHz for power lines 5–8) is delivered through coaxial lines with the characteristic impedance of 50 ohm. The power is measured by directional couplers near transmitters. The liquid impedance matching device with a three-stub-tuner is positioned approximately 30 m away from directional coupler to match the antenna load with characteristic impedance of transmission line. For each line, two pairs of V/I probes are installed near antenna approximately 3 m from feed-through, the two pairs are positioned $\Delta L \cong \lambda/4 \cong 2.2$m in space. Another two pairs of probes are positioned approximately 5 m from the stub tuners, also with distance of 2.2 m between each set of probes. The schematic diagram of ICRF system is shown in Fig. 1. Note that in antenna side and stub tuner side, the distance of the two V/I probes are 2.2 m apart, the reason is to avoid the case of two sets of probes all locating at the standing wave node where one probe would measure a maximum while the other one would measure a minimum, which leads to large errors in phase or amplitude measurements.

For each set of probes, the voltage and current probes are positioned on the same location along power transmission direction (see Fig. 2). A −6 dB[1] power splitter is connected to each voltage and current probe to split wave signal into two waves. One is sent to measure its amplitude read by RF detector, the other one goes to one of the input ports of phase detector, so that phase detector reads the phase difference between voltage and current probes. All the signals are acquired by National Instruments (NI) Corporation's USB-6363 acquisition card synchronously, the maximum sampling rate reaches 10 kS/s, satisfying the requirements of impedance measurement during fast plasma oscillation phenomena, such as Edge Localized Modes (ELM) [7].

3. Electromagnetic analysis and calibration of the V/I probes

The current probe consists of a copper loop that the magnetic field fluctuations induce a current flowing through a resistance of which potential difference V_a at each terminal is measured (Fig. 3a). The voltage probe consists of a disk installed perpendicularly to the cross section of coaxial line. The capacitance C_1 is formed between the disk and the inner conductor, and C_2 is formed between the disk and the outer conductors of coaxial transmission line (Fig. 3b). Voltages V_a and V_b of the probes signals can be expressed respectively as [8]:

$$V_a = \pm M \cdot dI/dt = \pm M \cdot j\omega I \quad (1)$$

$$V_b = V \cdot (R//X_{C2})/(R//X_{C2} + X_{C1}) \quad (2)$$

Here, I and V are the complex current and voltage of the transmission line, respectively. M is the mutual inductance between current probe and inner conductor, X_{C1} and X_{C2} are the capacitive reactance of C_1 and C_2, respectively.

One notes that the coupling coefficients of voltage and current probes are main parameters for calibration and impedance calculation,

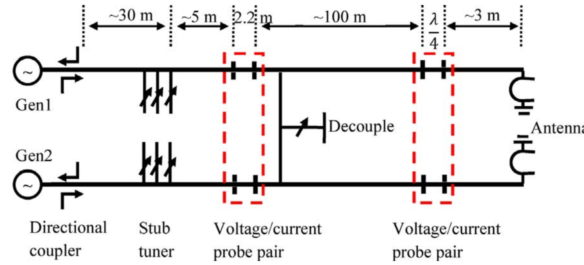

Fig. 1. Schematic diagram of two (of eight) EAST-ICRF transmission networks. The distance between two sets of probe pairs is about 2.2 m.

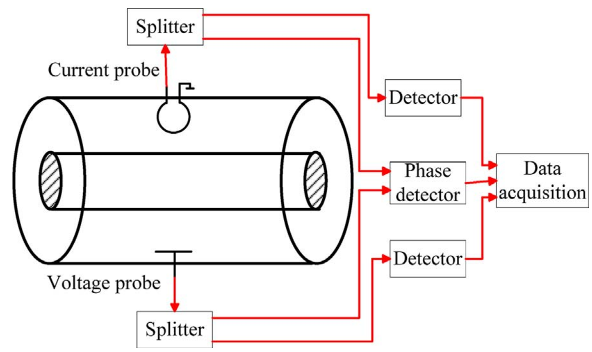

Fig. 2. Schematic diagram of the impedance measurement network of the ICRF system. The acquired RF signals from V/I probes are divided into two ways. All RF signals are converted to DC signals before being sent to the acquisition card.

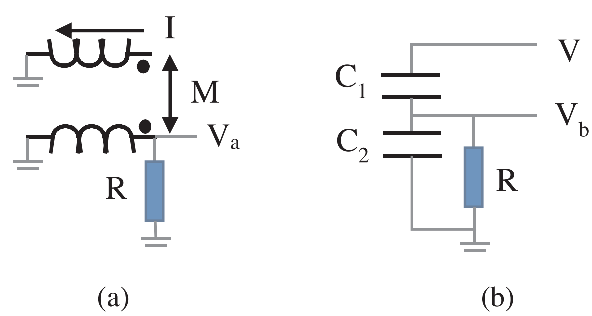

Fig. 3. Circuit map of V/I probes for circuit of (a) current probe and (b) voltage probe.

and they are both complex numbers containing amplitude and phase. The probe signals can be expressed as:

$$|V_{line}| = |V_{uprobe}|/K_{uprobe} \quad (3)$$

$$|I_{line}| = |V_{iprobe}|/K_{iprobe} \quad (4)$$

$$\varphi_{UI} = \varphi_{probes} - \varphi_0 \quad (5)$$

Where, V_{line}, I_{line} are the magnitude of voltage and current of transmission line, respectively. φ_{UI} is the phase difference between voltage and current. K_{uprobe} and K_{iprobe} are attenuation coefficients of voltage and current probes. φ_0 is the inherent phase difference between V probe and I probe. V_{uprobe}, V_{iprobe} and φ_{probes} are the measured voltages of each probe and the phase difference between them.

For a probe, the amplitude of coupling coefficient increases with the frequency. For a pair of V/I probes, the phase difference (φ_0) varies linearly with increased frequency and is close to 0° or 180° depending on the structure of the current probe and the direction of wave propagation. A typical current probe attenuation is depicted in Fig. 4, the results made by simulation show good agreement with that of the measurement using vector network analyzer. Fig. 5 shows the phase difference between V/I probes for simulation and calibration. Notice that the deviation between the two results is non-negligible. At 35 MHz, the deviation is 3° and it increases with the frequency. The main reason

[1] The power splitter used in EAST contains power loss within the electrical elements, the output/input voltages rate is 1/2, thus leads to −6 dB of amplitude attenuation.