Study of the Antenna Loading Resistance of the LHD ICRF Antenna

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Ion cyclotron range of frequencies (ICRF) heating is used to heat plasma in magnetically confined fusion plasma experiments. ICRF heating has been used in the Large Helical Device (LHD) and contributes to high-power steady-state experiments. Antenna loading resistance is important in ICRF heating; a high loading resistance is required for high-power injection. Many elements influence the antenna loading resistance. Here, the dependence of the loading resistance on various parameters is investigated. The loading resistance is very low at lower wave frequencies. High-power injection using such frequencies was difficult in plasma heating experiments in the LHD. The loading resistance increases with the plasma density. The distance between the antenna and the plasma boundary is closely related to the plasma edge density. It is important to keep the antenna away from the plasma and also keep the loading resistance at a certain level in steady-state operation for the various types of plasma. The effect of additional heating and magnetic field strength are also investigated. These results will contribute to the design of new ICRF antennas, the ICRF heating experiment in the LHD, and ICRF heating in future plasma devices.

Keywords: ICRF heating, LHD, helical device, loop antenna, loading resistance

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1. Introduction

Ion cyclotron range of frequencies (ICRF) heating is one of the most attractive means of additional heating for thermonuclear fusion plasmas. Various heating modes can be obtained by changing the wave frequency and magnetic field strength. Ions or electrons can be heated by selecting an appropriate heating scheme. In the Large Helical Device (LHD) [1], ICRF heating has been used as auxiliary heating and has contributed to high-power steady-state experiments [2, 3].

High-power steady-state operation of the transmitters and transmission line became almost possible with the hardware development achieved by the National Institute for Fusion Science (NIFS) [4–6] and others. Launching high power into the plasmas is still problematic. The number of ports in an experimental plasma device is limited. High power must be injected using antennas; and building high-power antennas is also one of the main concerns for ITER [7].

To inject high power into the plasma, a high antenna loading resistance is required to reduce the voltage of the transmission line and prevent arcing. The antenna loading resistance R is determined by

$$P = \frac{1}{2} R \left(\frac{V_{\mathrm{max}}}{Z_0} \right)^2 . \quad (1)$$

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P is the plasma injection power defined as the forward power minus the reflected power measured by a directional coupler. V_{max} is the maximum voltage of the transmission line measured by a voltage probe. Z_0 is the characteristic impedance of the coaxial line, which is 50 Ω. It is important to build high-loading-resistance antennas and operate them under experimental conditions in which high loading resistance is achieved. However, heating with a high loading resistance is not necessarily efficient. To improve the plasma parameters, efficient high-power heating is required.

Many elements influence the loading resistance. For example, the plasma density in front of the antenna is very important. The structure of the plasma edge region in a helical device is different from that in a tokamak device. The connection length of the magnetic field lines in the plasma edge region is much longer and the scrape-off layer is thicker in a helical device. The loading resistance has been investigated in several tokamak devices [8–12]. It would be interesting to determine the characteristics of the loading resistance in a helical device experimentally.

The loading resistance of the LHD ICRF antenna was investigated in various plasma heating experiments. These results will contribute to designing the operating scenario for high-power injection and provide suggestions for building new antennas.

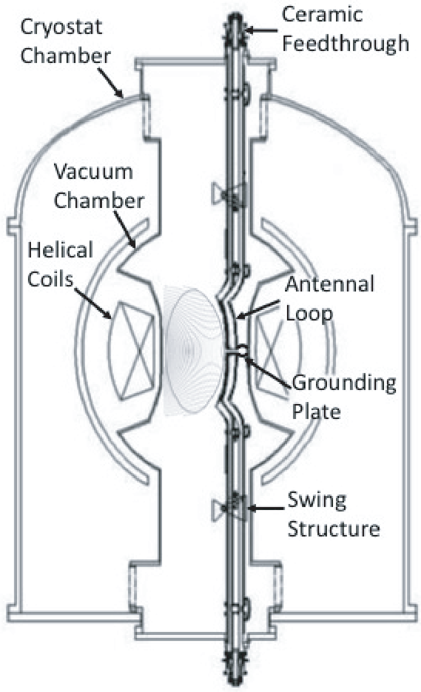

Fig. 1 Cross-sectional view of LHD and ICRF antennas. Center of the torus is located on the left. Flux surfaces and mod-B contours are also plotted.

2. Experimental Setup

The LHD is a superconducting helical device equipped with a neutral beam injection (NBI) heating system and an electron cyclotron heating (ECH) system in addition to the ICRF heating system. Figure 1 shows a schematic view of the LHD and the ICRF antennas. The antennas are installed at the upper and lower vertical ports and are located at the 3.5, 4.5, and 7.5 ports. They are named after their locations: "3.5U" for the upper antenna at the 3.5-port, for example. The antenna launches a fast wave outboard of the torus on the higher-magnetic-field side. The front surface of the antenna is twisted to fit the plasma's last closed flux surface (LCFS). The length, width, and strap width of the antenna are 0.6 m, 0.46 m, and 0.3 m, respectively, as shown in Fig. 2. The antenna can be moved about 0.15 m in the radial direction. Water cooling is available for long pulse operation.

The antenna is connected one-to-one to a high-power steady-state transmitter [4]. A liquid stab tuner [5] is used for the impedance-matching system in steady state operations. The wave frequency can be varied between 25 and 100 MHz.

Many experiments have been performed with a magnetic axis of 3.6 m and magnetic field strength at the axis of 2.75 T. The wave frequency is 38.47 MHz. The plasma is helium mixed with hydrogen as a minority ion species. The hydrogen ion cyclotron resonance layers are located at the saddle point of the magnetic field configuration [2, 3]. Off-axis minority ion heating is predicted, and the heating efficiency is optimized in the experiments.

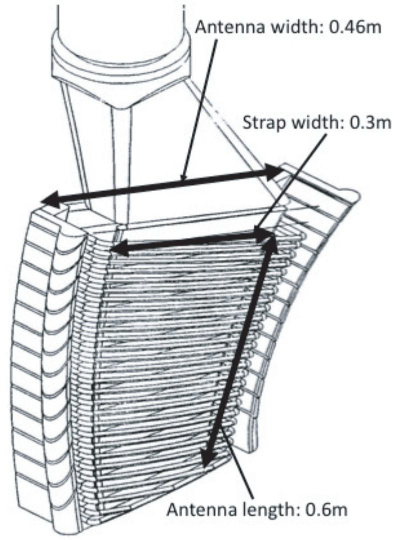

Fig. 2 Schematic drawing of the radiating part of the antenna.

If the wave frequency is lowered to 28.4 MHz in the same magnetic field, the ion cyclotron resonance layer moves to the plasma peripheral region, and the ion heating weakens. A mode-converted ion Bernstein wave (IBW) becomes important, and electron heating by the IBW becomes the main heating mechanism [13]. A ratio of hydrogen ions to plasma ions of more than 60% is required to place the mode-conversion layer within the half-radius of the plasma and obtain effective heating in the calculation.

Second-, third-, and higher harmonic heating can be obtained by increasing the wave frequency and/or decreasing the magnetic field strength.

3. Experimental Results

A large amount of data was collected for the six antennas. However, data analysis focused on a single antenna, 3.5U, to determine its characteristics. Figure 3 shows the frequency dependence of the loading resistance. Various conditions such as density range and the presence or absence of NBI heating are examined. The gap between the front of the antenna's Faraday shield and the plasma's LCFS is 8 to 11 cm. At the lower boundary of the data, a peak appears around 50 MHz. Similar characteristics are found by a calculation assuming a simple antenna model [14] and a simulation using the electromagnetic analysis code HFSS [15]. Expanding the data to the higher-loading-resistance region shows the possibilities for improvement. At 28.4 MHz, it was very difficult to inject high power during plasma experiments. This low loading resistance is thought to be caused by the relatively short electrical length of the antenna to low-frequency wavelengths. The antenna is optimized for the higher-frequency region, and its inductance and impedance are relatively low in the lower-frequency region. High voltage was required at the transmission line, and the voltage frequently reached the threshold of the interlock level when the injection power

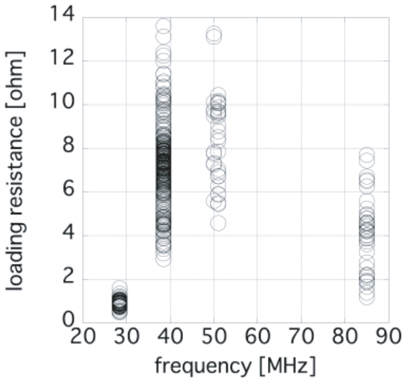

Fig. 3 Loading resistance versus wave frequency. Data are from the 3.5U antenna. Antenna gap is kept between 8 and 11 cm.

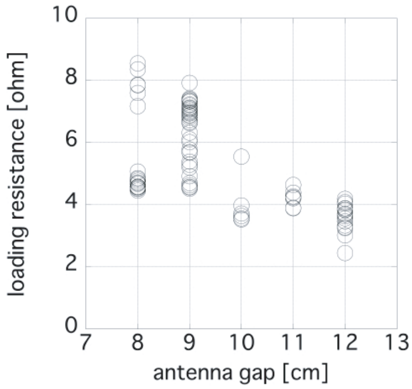

Fig. 4 Loading resistance as a function of the gap between the antenna surface and the LCFS. Data are from the 3.5U antenna, at 38.47 MHz, without NBI. Line-averaged electron density is kept between 0.5 and $1.5 \times 10^{19}\,\mathrm{m}^{-3}$.

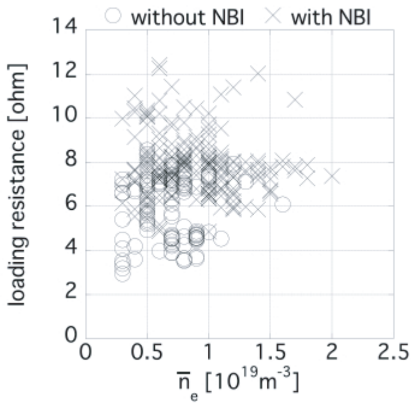

Fig. 5 Loading resistance versus line-averaged electron density. Data are from the 3.5U antenna at 38.47 MHz. Antenna gap is kept between 8 and 11 cm.

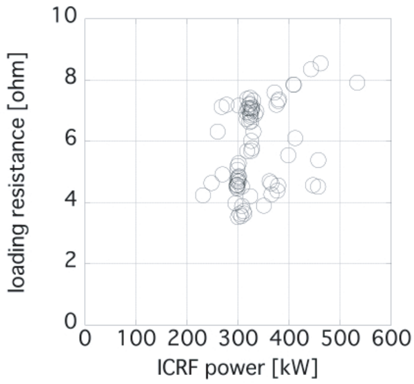

Fig. 6 Loading resistance versus injected ICRF power. Data are from the 3.5U antenna at 38.47 MHz without NBI. Line-averaged electron density is kept between 0.5 and $1.5 \times 10^{19}\,\mathrm{m}^{-3}$. Antenna gap is kept between 8 and 11 cm.

was increased. The antenna design and transmission line must be modified if this frequency is to be used for high-power heating.

The antenna must be operated far from the plasma during steady-state operation to reduce heat load from the plasma. The loading resistance versus the gap between the antenna and the plasma is shown in Fig. 4. The wave frequency was 38.47 MHz, and the line-averaged electron density ranged from 0.5 to $1.5 \times 10^{19}\,\mathrm{m}^{-3}$. NBI heating was not applied. The loading resistance decreases with increasing antenna gap distance, as expected. For steady-state operation, the antenna gap was set to 12 cm. A loading resistance of $4\,\Omega$ is possible in this case. If a voltage of 35 kV is allowed for the coaxial line, an injection power of 1 MW is possible. A similar loading resistance has been obtained in tokamak experiments such as JET [8], TFTR [9], and JT-60U [10], although the configuration of the antenna is different. The RF frequencies used in JET, TFTR, and JT-60U were 33, 32, and 116 MHz, respectively. The loading resistance values are several ohms at an antenna gap of around 10 cm in their respective heating conditions.

Figure 5 shows the loading resistance versus the line-averaged electron density with and without NBI heating. Open circles represent data without NBI heating, and crosses show data with NBI heating. The lower boundary of the data shows the density dependence of the loading resistance. The loading resistance increases with the plasma density, and the same dependence was found as in tokamak experiments [10, 11]. With NBI heating, the lower boundary moves upward, and a higher loading resistance is easily obtained. This shows the modification of the plasma boundary condition by NBI heating. The density in front of the antenna may increase. This enhancement of the loading resistance is also found with ECH. For high-power heating, it is preferable to inject the ICRF power with additional heating.

Figure 6 shows the loading resistance versus the injection power. The line-averaged electron density ranges from 0.5 to $1.5 \times 10^{19}\,\mathrm{m}^{-3}$, and the antenna gap is 8 to 11 cm. The low-power data require precise analysis because some shots are not good. Thus, they are removed from the analysis for the moment. No power dependence

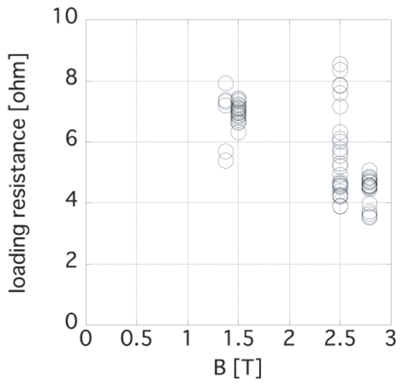

Fig. 7 Loading resistance versus strength of magnetic field. Data are from the 3.5U antenna at 38.47 MHz without NBI. Line-averaged electron density is kept between 0.5 and 1.5×10^{19} m^{-3}. Antenna gap is kept between 8 and 11 cm.

appears at powers higher than 200 kW. Tokamak experiments such as TEXTOR [11] and DIII-D [12] also found almost no power dependence at powers of 200 to 600 kW.

Various experiments were performed with a varying magnetic field. The loading resistance versus the magnetic field is shown in Fig. 7. The ion cyclotron resonance layers are located at the magnetic axis in a magnetic field of 2.5 T. A magnetic field of 1.375 T is half the standard magnetic field of 2.75 T. Thus, second-harmonic heating is expected in this case. The lower boundary of the data is higher with a lower magnetic field. There is some possibility of high-power injection with second- and higher harmonic heating. However, the mechanism for the increase in the loading resistance is not clear.

The upper and lower antennas in the LHD ICRF antenna are closely related. In the future, we will investigate the influence of interactions between the antennas, such as phasing effects, on the loading resistance.

4. Summary

The loading resistance of the LHD ICRF antenna was investigated. A relatively strong frequency dependence appears for the existing antenna. At a frequency of 28.4 MHz, the loading resistance is extremely small, and some modification of the hardware may be required for high-power injection. The loading resistance decreases with increasing antenna-plasma gap. The loading resistance is still high enough at a gap distance of 12 cm, where the antenna was operated in the steady-state experiments. The loading resistance increases with the electron density. Additional heating such as NBI enhances the loading resistance. The loading resistance also increases at a lower magnetic field. Thus, high-power injection may be possible with second- and higher harmonic heating. These experimental results provide clues to high-power injection in the ICRF heating scenario and the new antenna design.

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