Steady State Test at High RF Voltage on Transmission System for Ion Cyclotron Heating

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Abstract

Ion Cyclotron Range of Frequency (ICRF) heating on Large Helical Device (LHD) is characterized by its high power (up to 12 MW) and by steady state operation (30 minutes). The LHD is a helical device (with a major radius of 3.9 m and a minor radius of 0.6 m) with super-conducting coil windings ($l = 2$, $m = 10$). The main physical purpose is to investigate currentless and disruption-free steady state plasmas. Research and development for ICRF heating have been carried out in recent years. A high RF power transmission system has been developed, which consists of stub tuners, ceramic feed-through and ICRF heating loop antenna.

The RF transmission system was tested and withstood 58 kV for 10 seconds and 40 kV for 30 minutes. The RF voltage corresponds in the case of a plasma loading resistance, 5 Ω to a transmitted RF power capability of 3.4 MW and 1.6 MW. In addition, a pre-matching stub tuner was very effective in reducing the RF voltage. The reduction rate was confirmed to be one third, which leads to a higher ICRF injection efficiency because of reduction of RF power loss in the transmission system. Furthermore a proper procedure to effectively carry out aging of the RF antenna was found in terms of selecting the RF pulse length, repetition rate and RF voltage.

Keywords:

ICRF heating, high RF power, steady state heating, pre-matching stub tuner, antenna aging

1. Introduction

Research and development for steady state Ion Cyclotron Range of Frequency (ICRF) heating have been carried out at the National Institute for Fusion Science. Steady state ICRF heating will be applied to the plasma at the high power on the Large Helical Device (LHD, with a major radius of 3.9 m and a minor radius of 0.6 m) [1-4]. The LHD is a helical device with super-conducting coil windings ($l = 2$, $m = 10$). The main physical research is to investigate currentless and

disruption-free steady state plasmas. Heating by neutral beam injection (NBI) produced the high performance of the plasma, which was initiated by 2nd harmonic electron cyclotron heating (ECH, 84 GHz) at the magnetic field strength, 1.5 T in 1998 [5,6]. The preliminary ICRF heating was applied to the ECH plasma at 200–300 kW of RF power. The increment of the plasma stored energy was observed at the same level of that in ECH plasma. In helical and stellarator systems, the ICRF heating could not always demonstrate

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successful heating [7-9]. The ICRF-heated plasma often suffered from impurity problems. However ICRF heating was successfully applied to Compact Helical System (CHS) [10-13] and Wendelstein (W7-AS) [14-16] with the aid of Boronization. The surface of the plasma vacuum wall of the LHD was conditioned by a discharge cleaning of He glow or ECR (2.45 GHz) plasma. The impurity accumulation was not observed at the ICRF heating.

ICRF heating will be applied to the LHD plasma at 12 MW for several seconds and in steady state at 3 MW, for which research and development have been carried out since 1993. First an RF oscillator system with a wide frequency range was designed and fabricated. ICRF heating has many scenarios such as two-ion-hybrid heating, minority heating, ion Bernstein wave (IBW) heating and higher harmonic heating. Furthermore as the experimental magnetic field strength will be changed from 1 T to 4 T, the frequency has been determined to cover from 25 to 100 MHz. The steady state operation (5,000 seconds) was achieved at an output RF power of 1.6 MW by operating the tetrode tube in a low impedance mode to reduce the screen grid current and ion pump current [17]. In parallel with the development of the RF oscillator, an ICRF heating loop antenna and an RF power transmission system were tested for steady state ICRF heating, consisting of stub tuners, a ceramic feed-through and a DC break. Two types of ceramic feed-throughs could withstand the RF voltage of 40 kV at the steady state operation; one was a cone shaped type (Al_2O_3) and the other was a cylindrical silicon nitride (Si_3N_4) ceramic [18,19]. A liquid stub tuner was developed as an innovation, which substitutes a conventional stub tuner with movable sliding contact. The liquid stub tuner was verified to be a reliable RF component [17,20].

In this paper, a steady state test at the high RF voltage on the transmission system is reported. The goal of the test was to prove that the transmission system could withstand 45 kV for 10 seconds and 40 kV for 30 minutes. In this test, the vacuum pressure was found to play an important role. To achieve a successful steady state operation at the high RF voltage, a proper aging of RF antenna was required. In Sec.2, the experimental setup will be described. In Sec.3, experimental results are presented. In Sec.4, we will discuss experimental data. Then we will conclude in Sec.5.

2. Experimental Setup

A schematic drawing of the R&D experimental setup is shown in Fig.1. The RF oscillator system consists of three stages of amplifiers, i.e. IPA (4 kW), DPA (100 kW) and FPA (2 MW). The final power amplifier (FPA) is composed of a 4 m long double-coaxial cavity and has a capability to generate 2 MW for several seconds and 1.5 MW in steady state in the frequency range, 25–100 MHz. RF power operations were achieved at 2 MW for 10 seconds and 1.6 MW in steady state (5,000 seconds) at 50 MHz [17]. In this experimental setup, the RF power was transmitted to a dummy load or the R&D experimental setup through a co-axial switch. The experimental setup was sometimes changed as described later, so this system was very convenient. A small RF power of several Watts was applied from one port of the co-axial switch to acquire an impedance matching. Then the RF oscillator was tuned to maximize an output power at the frequency. The whole transmission system consists of coaxial transmission line components of 240 mm ϕ whose characteristic impedance is 50 Ω . A cross section of the transmission line is shown in Fig.2(a). Cooling water flows inside the inner conductor, and copper tubes cooled by water surround the outer conductor at the place where RF power loss was relatively large, e.g. at the high RF current position and at the liquid stub tuner. Figure 2(b) shows a detailed structure at the joint of two transmission lines. This part was carefully designed and fabricated to ensure no water leakage and have a tight electrical contact. The inner conductor tip is sealed by O-ring. A contact finger plate (made by Multi-Contact Co.) is used for the tight electrical contact. The outer conductors are connected at the flange. A tip of the inner conductor with a O-ring is inserted into the other tip as shown in Fig.2(b). Therefore these transmission lines are demountable. For several years of the test, no water leakage has been found. A recess structure was chosen to reduce the local RF electric field at the corner edge of a Teflon insulator as shown in Fig.2(b).

A double stub tuner system was adopted as an impedance matching circuit. The conventional stub tuner was used on the RF oscillator side. It has a sliding contact. A mechanism actuated by an air cylinder was adopted in the movable sliding contact. When it was moved, the tight contact becomes slack by pressurized air. The liquid stub tuner was arranged on the RF antenna side as shown in Fig.1. The RF voltage is much higher there than on the RF oscillator side. The reason why the liquid stub tuner was located there was that

R&D experiments have shown that it is more reliable than a conventional stub tuner. The idea of the liquid stub tuner is based on the difference between the RF wave length in the liquid and in the gas due to the different relative dielectric constant. It is shown in Fig.3. Silicon oil (Dimethyl Polysiloxane) was used as liquid. The liquid stub tuner is able to act as a conventional stub tuner by changing the liquid surface level instead of moving the sliding contact (electrical short-end). This idea is also applicable to a liquid phase shifter. A relation between the liquid and the conventional stub tuners is expressed in the following equation [20],

$$\frac{1}{\tan 2\pi A_s} = \frac{1 - Z_L/Z_0 \tan 2\pi A_{GS} \tan 2\pi A_{LS}}{\tan 2\pi A_{GS} + Z_L/Z_0 \tan 2\pi A_{LS}} \quad (1)$$

A_s is the resultant length of the liquid stub tuner. Z_0 and A_{GS} are the characteristic impedance of a coaxial transmission line and the normalized length by the RF wave length in the gas region, respectively. Z_L and A_{LS} are the characteristic impedance and the normalized length by the RF wave length in the liquid, respectively.

The relative dielectric constant of the liquid is $\epsilon_L = 2.72$. The ratios of the characteristic impedance and the RF wave length are $Z_L/Z_0 = \epsilon_L^{-1/2}$ and $\lambda_L/\lambda_0 = \epsilon_L^{-1/2}$ in (1). When the normalized length of the liquid stub tuner is 0.3, the variable range of the liquid stub tuner is from 0.3 to 0.5. The operating range becomes wider with the liquid stub tuner length.

A pre-matching stub tuner (see Fig.1) was located between the ceramic feed-through and the impedance matching circuit in order to reduce the maximum voltage of the standing RF wave. The reduction of the RF voltage leads not only to a reduction in the Ohmic loss, but also to an improvement in reliability from the view point of avoiding an RF breakdown on the transmission system. The ceramic feed-through was located between the pre-matching stub tuner and the ICRF heating antenna. It was tested at high RF voltage in the steady state operation. The test results are described in other papers [18,19]. In a vacuum tank, an ICRF heating loop antenna was installed, which was a prototype antenna 430 mm wide and 630 mm long.

The RF power was transmitted to the RF antenna through a co-axial switch and a DC break. The DC

Fig.1 Layout of the experimental setup for testing the high RF power transmission system for ICRF heating. RF power is transmitted from the final amplifier to the test section through co-axial switch and DC break. A liquid stub tuner is located at the RF antenna side of the impedance matching circuit, which consists of a double stub tuner. A pre-matching stub tuner is located between the ceramic feed-through and the impedance matching circuit.

break was designed and fabricated to withstand an isolation voltage of 10 kV and to reduce the leaking RF power to 60 dB. The whole structure is illustrated in Fig.4(a). The length and the diameter are 1,800 mm and 465 mm, respectively. The detailed structure is shown in Fig.4(b), which is expanded from the inside of the circle in Fig.4(a). The inner conductor is a ceramic capacitor, which is 4.5 mm in thickness and 450 mm in length. Both surfaces were coated with a silver (Ag) at a thickness of 10 μm . Several Ag-coated copper rings are attached to reduce RF resistance on both side of the ceramic capacitor. The outer transmission is composed of two outer conductors, which are isolated by 6 layers of thin Kapton sheets (125 μm). The leaking RF electric field was measured at several positions during RF operation at the applied power of 100 kW. The measured RF electric field was 2 mV/m at a position 3 m away from the DC break. The RF electric field was much lower than the one allowed by ICNIRP (International Commission on NonIonizing Radiation Protection). When the RF power of 2 MW is applied at

the transmission system, the RF electric field is deduced to be 10 mV/m near the DC break, which is still much lower than the one allowed by ICNIRP, 30 V/m.

When the maximal RF voltage of the standing wave is achieved at 40 kV and 45 kV, the RF power transmission capability is deduced to be 1.6 MW and 2 MW, respectively in the case of a plasma loading resistance of 5 Ω . The final goal of the research and development was the achievement of 40 kV for 30 minutes and 45 kV for 10 seconds. In this experiment, the loading resistance was 0.4 Ω because of the absence of plasma, so the high RF voltage as stated above was attained with a relatively low RF power, 128–168 kW. The above-mentioned goals could be achieved; however, the high RF voltage tests were sometimes interrupted by a higher vacuum pressure than 1×10^{-5} Torr.

3. Experimental Results

3.1 Aging procedure of RF antenna

The vacuum pressure increased due to outgassing gas caused by a multipactoring discharge during an

Fig.2 (a) Schematic drawing of coaxial transmission line, 240 mm ϕ for steady state ICRF heating. (b) Cooling water flows inside inner conductor. Teflon spacer has a recess structure to decrease the RF electric field at the corner edge of inner conductor.

operation of high RF power. High vacuum pressure impeded high RF voltage operations. Two critical vacuum pressures were found experimentally to lead to the successful long pulse operations; one was 1×10^{-6} Torr just before applying RF power, and the other was 1×10^{-5} Torr during the high RF voltage operation. When the vacuum pressure was higher than 1×10^{-6} Torr at the beginning of the pulse, the high RF voltage was not applied because the reflected RF power fraction exceeded half. In addition, the long pulse test at the high RF voltage was sometimes interrupted by the vacuum pressure higher than 1×10^{-5} Torr.

Aging of ICRF heating antenna and the transmission line in the vacuum is essential to carry out a high RF voltage test on the whole transmission system. Two different methods were tried to find an appropriate procedure to aging; the RF power was applied at a low repetition rate, *e.g.* every 50 or 100

seconds. The other was a high repetition rate, *e.g.* every 0.1–1 second. In the former method, the fraction of reflected RF power was almost zero and the applied RF voltage was high, because the vacuum pressure was lower than 1×10^{-6} Torr at the beginning of the pulse. In the latter case, the impedance matching was not attained. The vacuum pressure was $3\text{--}4 \times 10^{-6}$ Torr during the aging procedure. As the RF voltage was small, the position of the multipactoring discharge was different from that in the high RF voltage operation, which will be discussed in Sec.4.2. This method was determined to be inappropriate to the aging procedure, although this degassing process seemed to be adequate because of the high vacuum pressure.

The low repetition rate aging was adopted for aging the RF heating antenna and the transmission line in the vacuum. The vacuum base pressure was 2×10^{-7} Torr. In the beginning of the series of aging procedures, a

Fig.3 Schematic drawing of the liquid stub tuner, consisting of 240 mm² of coaxial transmission line. The liquid stub tuner is connected at T junction in the transmission system. Silicon oil (Dimethyl Polysiloxane) is used as liquid. The liquid surface level can be changed by oil pump and valves.

Fig.4 (a) Sectional drawing of the DC break, which was designed to withstand 10 kV of isolation voltage and to reduce RF power leakage to less than 60 dB. (b) Detailed structure of the DC break. Inner conductor consists a ceramic capacitor, which is coated by thin silver. Thin Kapton sheet is inserted between outer conductors.

relatively low RF voltage, *e.g.* from 20 to 30 kV was applied at the short pulse length, *e.g.* from 0.01 to 0.05 second. Then the applied RF voltage and the pulse length were gradually increased. It took 5 or 6 hours to finish aging. Figure 5(a) shows a typical time evolution of the vacuum pressure in aging for about one and half hours (4,850 seconds), which was carried out at the final stage in the series of aging procedures. The RF power was applied at $V_{RF} = 46.6$ kV for 0.2 second every 50 seconds. A lower and a higher envelopes of the vacuum

Fig.5 (a) Time evolution of vacuum pressure during aging RF antenna and transmission line in vacuum for 5,000 seconds. The applied RF voltage was increased from 46.6 kV to 54 kV. The RF power was applied for a pulse length of 0.2 second in every 50 seconds. (b) Time evolution of vacuum pressure during aging RF antenna and transmission line in vacuum from 3,250 to 3,750 seconds, which is expanded from Fig.5(a). When the vacuum pressure was higher than 1×10^{-6} Torr just before applying RF pulse at 3,550 seconds, RF voltage was low and the vacuum pressure increase was smaller than that of normal aging shot.

pressure were ones just before and after the RF pulse, respectively. The difference of two values indicated the outgassing quantity. The increase in the vacuum pressure due to outgassing gradually decreased shot by shot. The main outgassing gas was hydrogen. During the aging procedure, the RF voltage was increased from 46.6 kV to 54.0 kV in 3 steps; about 5% increase in each step. A lower envelope of the vacuum pressure was a key monitor in the aging procedure. It reached the maximum after a few shot, gradually decreased and did not exceed 1.3×10^{-6} Torr as shown in Fig.5(a). After the aging procedure, a steady state operation at $V_{RF} = 40$ kV was achieved, which will be discussed in Sec.3.3.

The time span from 3,250 to 3,750 seconds of Fig.5(a) is expanded in Fig.5(b). The vacuum pressure reached the maximum 5 seconds after applying the RF power. The vacuum pressure decayed with a time constant of 40 seconds (a reasonable number by taking into account the capacity of the vacuum tank, 20 m³ and a vacuum pumping effective speed, 0.5 m³/sec). When the vacuum pressure was higher than 1×10^{-6} Torr just before applied RF power, the high RF voltage was not sometimes applied as seen at 3,550 seconds (pointed by arrow in Fig.5(b)). In this shot, the pressure increase was much smaller than that during normal aging shots because the impedance matching was lost. The careful selection of the pulse length of applying RF power, the repetition rate and the RF voltage was required for the vacuum pressure not to exceed 1×10^{-6} Torr just before applying RF power.

We will find a different aging procedure for the ICRF heating antenna installed to LHD. As the capacity of LHD is 200 m³ and the vacuum pumping speed is 43 m³/sec (hydrogen), the best aging procedure will be found at a longer RF pulse length and a higher repetition rate than those in the present procedure. Aging is expected to finish faster than in the present case.

3.2 Frequency feedback control for high RF voltage and long pulse test

In the long pulse test on the transmission system at the high RF voltage, the reflected RF power increased with time. When the RF power was applied in absence of a feedback control at the impedance matching, the reflected RF power, P_{ref} exceeded half the forward power, P_{fw} within one minute and the RF voltage, V_{RF} declined consequently. On the other hand, P_{ref} could be kept at a low fraction of P_{fw} and V_{RF} was constant using the feedback control. Here the RF voltage means the maximal voltage in the standing wave. The RF voltage

was measured by electrostatic probes at several positions between the RF antenna and the impedance matching circuit as will be described in Sec.3.4. The RF power supply would be turned off to protect the tetrode tube in the final amplifier by an interlock system, if the feedback control method is not used in the experiment.

The feedback control of the impedance matching was done with frequency modulation. The time evolution of the modulated frequency is shown with P_{fw} and P_{ref} at $V_{RF} = 40$ kV in Fig.6. The frequency was 47.998 MHz at the beginning of the shot and decreased by 2% after 2 minutes. Then the modulated frequency gradually increased a little and became constant at $f = 47.080$ MHz. In spite of the large modulated frequency, $df/f = 2\%$, the forward power was kept at the same level by an Automatic Level Control (ALC) method. The fraction of the reflected RF power increased to 2.5% due to losing the impedance matching, which indicated that the complete impedance matching could not be attained with frequency modulation only.

The required modulation rate of the applied frequency increased with the applied RF voltage. In all experiments, the minimal frequency was always found after 2 minutes at various applied RF voltages. The dependence of the required modulation rate on the applied RF voltage is plotted in Fig.7. It is roughly proportional to a square of the applied RF voltage, which suggests that a thermal expansion of the transmission system based on the Ohmic loss causes the required frequency modulation. As indirect evidence, the dependence of the impedance matched frequency on a deformation of the transmission line was examined by changing a pressurized gas, from vacuum to 4 kg/cm². This experiment showed that the frequency changed with the filling pressure, which was further corroborative evidence.

3.3 Vacuum pressure increase during long pulse operation

An aging of the ICRF heating antenna and the transmission line in the vacuum could mitigate a pressure increase during long pulse operation at high RF voltage. The vacuum base pressure was 2×10^{-7} Torr. Figure 8 shows a typical time evolution in the long pulse test at $V_{RF} = 40$ kV. In this operation, the applied RF power was $P_{fw} = 124$ kW. There were two levels of the critical vacuum pressure as described in the previous section, Sec.3.1. The pressure should be lower than 1×10^{-6} Torr at the beginning of the long pulse test, which condition was easily satisfied. The pressure exceeded

Fig.6 Time evolution of applied frequency, forward RF power, P_{fw} and reflected power, P_{ref} and RF voltage, V_{RF} at 40 kV operation with frequency feedback control.

Fig.7 Dependence of the required change of frequency on the applied RF voltage.

Fig.8 Time evolution of increase in vacuum pressure, forward RF power, P_{fw} and RF voltage, V_{RF} at 30 minutes operation.

the critical value of 1×10^{-6} Torr at 470 seconds; however, an increase in the reflected RF power was not observed. The pressure continuously increased with time to 6×10^{-6} Torr at the end of RF power pulse, 30 minutes. If the antenna aging was not enough, the vacuum pressure exceeded the critical value (1×10^{-5} Torr) and the RF breakdown occurred in the whole vacuum chamber. Then the RF power supply was turned off by the interlock system monitoring the reflected RF power.

3.4 RF voltage reduction by pre-matching stub tuner

The RF voltage was measured at 4 different positions along the transmission line between the RF antenna and the double stub tuner circuit. Figure 9 shows a typical distribution of the RF voltage in the case of $V_{RF} = 51$ kV and applied frequency, $f = 49.01$ MHz. In this figure, the abscissa is the distance between the measured position and T junction of the liquid stub tuner. The ceramic feed-through was located at 13.3 m. In this experiment, the high voltage test of the ceramic feed-through was conducted, so the position of the maximal RF voltage was located just there. A voltage reflection coefficient, Γ was deduced from the RF voltage distribution. In this experiment, the length of the pre-matching stub tuner was a quarter of the RF wave length, so the RF voltage reduction was not observed.

The best condition was searched for the pre-matching stub tuner. Selection of a distance between the RF antenna and the pre-matching stub tuner depends on how the pre-matching stub tuner can reduce the RF voltage. As the distance was constant, the largest reduction rate at the RF voltage was found by changing the applied frequency. The best condition was obtained in the case of $f = 47.472$ MHz. Figure 10 shows the RF voltage distribution, which demonstrated that the RF voltage was reduced to one third. The reduction rate of the RF voltage was $V_{RF}/V_{RF0} = 0.336$ at $A_p = 0.052$, where V_{RF0} and V_{RF} were 58 kV and 19.5 kV, respectively as shown in Fig.10. A_p is the normalized length of the pre-matching stub tuner. The dissipated RF power could be reduced to 10% of that at normal operation without the use of the pre-matching stub tuner. In the operation, the transmitted RF power, P_{fw} was 153 kW and the RF loading resistance (R_v) was reduced from 0.4Ω to 0.23Ω . The lower RF voltage reduces a risk of the RF breakdown on the transmission system. The lower loading resistance produces a higher ICRF injection efficiency, which is defined by a ratio of a

plasma loading resistance (R_p) to the total RF loading resistance, $R_p/(R_p + R_v)$.

The RF voltage reduction rate, V_{RF}/V_{RF0} was measured by changing the length of the pre-matching stub tuner, A_p . V_{RF}/V_{RF0} decreased with the decrease in the pre-matching stub tuner length as shown in Fig.11. When A_p was 0.25, the RF voltage reduction was not observed, i.e. $V_{RF}/V_{RF0} = 1.0$. The V_{RF}/V_{RF0} was reduced to 0.336 as a minimal value, at normalized length of the pre-matching stub tuner, $A_p = 0.052$. In this figure, the calculated RF voltage reduction rate is also plotted in a solid line, which will be discussed in the next section, Sec.4.1.

Fig.9 RF voltage distribution on the transmission system is shown at the operation of RF voltage, 51 kV. Distance, L was measured from T junction of liquid stub tuner. The maximal RF voltage was situated near the ceramic feed-through at 13.3 m.

Fig.10 A typical example of RF voltage distribution at RF transmission system. RF voltage is reduced to one-third by the pre-matching stub tuner; $V_{max0} = 58$ kV and $V_{max} = 19.5$ kV.

Fig.11 Dependence of reduction rate in RF voltage, $V_{\max}/V_{\max0}$ on the length of the pre-matching stub tuner, A_p . $V_{\max}/V_{\max0}$ is 1.0 and 0.036 at $A_p = 0.25$ and $= 0.052$, respectively.

3.5 Liquid stub tuner

The liquid stub tuner was located on the RF antenna side of the double stub tuner system. In the series of experiments, the same high RF voltage was applied at the liquid stub tuner as at the transmission system (confirmed by measuring the RF voltage at the liquid stub tuner). The RF voltage measurement method was the same as described before. It should be noted that the RF voltage measured in the liquid must be divided by the dielectric constant, $\epsilon_L = 2.72$. The RF wave length in the liquid was found to be shortened by a factor of the square of the dielectric constant. The liquid stub tuner was verified as satisfying our criteria, i.e. 45 kV for 10 seconds and 40 kV for 30 minutes. A further test was carried out to make sure the limits of the liquid stub tuner. The increase in the vacuum pressure interrupted the long pulse operation at the high RF voltage as described in Sec.3.3. To test the liquid stub tuner at higher RF voltage, the transmission line was disconnected at point A as shown in Fig.1. The liquid stub tuner could withstand 61.3 kV for 10 seconds and 50 kV for 30 minutes without breakdown. The performance of the liquid stub tuner is summarized in

Table.1. In addition, the liquid surface was able to be shifted at the high RF voltage operation, $V_{RF} = 46$ kV, which suggested that the feedback control using the liquid stub tuner is able to keep the reflected RF power at a low level against the temporal variation of the plasma loading resistance. The temperature increase in the liquid was 35°C at $V_{RF} = 50$ kV in steady state operation. The dissipation loss due to the dielectric loss was negligibly small, which is less than 1% of the forward RF power in the case of the plasma loading resistance, 5Ω [20].

3.6 Operational regime on high RF voltage and duration time

It is important to test how high an RF voltage and how long a pulse length the whole transmission line withstands without RF breakdown. Two criteria were set up; it could endure $V_{RF} = 45$ kV for 10 seconds and 40 kV for 30 minutes. These two duration times were derived from the pulse length at the ICRF heating experiments, which are 10 seconds at the high RF power (more than 10 MW by using several RF antennas) and 30 minutes at 3 MW (using two antennas), respectively. The two values of the RF voltage are equivalent to the capability of the RF transmitted power, 2 MW and 1.6 MW, respectively in one transmission system in the case of the plasma loading resistance, 5Ω . The long pulse operation was tested on the whole transmission system at the high RF voltage. The operation was often interrupted by the vacuum pressure increase as described in Sec.3.3. The multipactoring discharge caused the pressure increase, so the aging of the RF antenna was required as described before. When the condition of the RF antenna and the transmission line in the vacuum was not improved enough by aging, the long pulse operation could not be achieved due to the RF breakdown at a vacuum pressure higher than the threshold pressure, 1×10^{-5} Torr. There are several experimental data, which could not be maintained for 30 minutes as shown in Fig.12. In this figure, the highest RF voltages at 10 seconds and 30 minutes operation are 58 kV and 40 kV, respectively. The operation of $V_{RF} =$

Table.1 Experimentally Achieved Results in Liquid Stub Tuner.

Duration Time	RF Voltage	Capability of Transmission RF Power at Plasma Resistance, 5Ω	Liquid Temperature Increase
10 seconds	61.3 kV	3.8 MW	—
30 minutes	50 kV	2.5 MW	35°C

58 kV for 10 seconds was achieved using the pre-matching stub tuner as described in Sec.3.4. When the plasma loading resistance is 5Ω at the ICRF heating experiments on LHD, these achieved values were equivalent to the transmitted RF power of 3.4 MW and 1.6 MW, respectively. The high RF voltage test on the transmission system has proven that the achieved results exceed the criteria for RF voltage, *i.e.* 45 kV for 10 seconds and 40 kV for 30 minutes. Therefore the RF transmission system consisting of coaxial transmission line components of 240 mm ϕ is adopted in the ICRF heating system on the LHD.

4. Discussion

4.1 RF voltage reduction by pre-matching stub tuner

When ICRF heating is carried out at MW level at the plasma loading resistance of several Ω , an RF voltage of 40–50 kV will be applied between the RF antenna and the impedance matching circuit. The power is lost at a few kW per unit length, m due to the Ohmic resistance. The total power loss amounts to 100 kW in the long coaxial transmission system on LHD, which is estimated to be about 40 m long. This lowers the ICRF injection efficiency. In addition, the risk of RF breakdown increases at the high RF voltage operation. Use of the pre-matching stub tuner is a solution to both problems. It was located between the RF antenna and the impedance matching circuit. When it is located in a proper position and the length of the pre-matching stub tuner is selected well, the RF voltage is remarkably reduced between the pre-matching stub tuner and the impedance matching circuit. A reduction rate of the RF voltage by the pre-matching stub tuner was calculated using following equation.

$$\begin{pmatrix} V_L \\ I_L \end{pmatrix} = \begin{pmatrix} \cos 2\pi A_L & jZ_0 \sin 2\pi A_L \\ j/Z_0 \sin 2\pi A_L & \cos 2\pi A_L \end{pmatrix} \begin{pmatrix} 1 & 0 \\ j/Z_0 \tan 2\pi A_P & 1 \end{pmatrix} \begin{pmatrix} \cos 2\pi A_{AP} & jZ_0 \sin 2\pi A_{AP} \\ j/Z_0 \sin 2\pi A_{AP} & \cos 2\pi A_{AP} \end{pmatrix} \begin{pmatrix} V_A \\ I_A \end{pmatrix} \quad (2)$$

Figure 13 is a schematic drawing to illustrate the calculation model of the pre-matching stub tuner. Here

Fig.12 Experimentally achieved operational regime of transmission system in a plane of duration time and RF voltage, V_{RF} . High RF voltage operation of $V_{RF} = 58$ kV for 10 seconds was achieved in use of pre-matching stub tuner.

Fig.13 Schematic drawing to illustrate the function of the pre-matching stub tuner. V_{max0} is the maximal RF voltage between pre-matching stub tuner and RF antenna and V_{max} is the maximal RF voltage between pre-matching stub tuner and impedance matching circuit (left side).

V_L and I_L are the RF voltage and the current at any position, A_L , which is the distance from the pre-matching stub tuner. A_P is the length of the pre-matching stub tuner. A_{AP} is the length between the pre-matching stub tuner and the RF antenna. V_A and I_A are the RF voltage and the current at the ICRF heating antenna. Z_0 is the characteristic impedance of the transmission line. These lengths, A_L , A_P and A_{AP} are normalized by the RF wave length. The maximum voltage of the RF standing wave, V_{max} can be calculated along the transmission line by using the two quantities, V_L and I_L obtained in eq.(2). This value is compared with the maximal value of the RF standing wave between the pre-matching stub tuner and the RF antenna, V_{max0} . The RF voltage reduction rate of V_{max} to V_{max0} was calculated in two dimensional planes of A_{AP} and A_P . Figure 14 shows a calculated contour map of V_{max}/V_{max0} , where the abscissa and the ordinate are A_{AP} and A_P , respectively. Here it should be

Fig.14 Contour map of the reduction of the RF voltage. Abscissa is the length between RF antenna and the pre-matching stub tuner, A_{AP} and ordinate is the length of the pre-matching stub tuner, A_P . Calculated value along a dashed line was plotted in Fig.10 to compare with experimental data.

noted that the solution is periodic in every 0.5 of A_{AP} and A_P . The contours were plotted from 0.3 to 1.0. When A_P is 0.25, the RF voltage reduction was not obtained because the pre-matching stub tuner does not work. The value of A_{AP} was determined to be 0.445 using two experimental values of the RF voltage at the pre-matching stub tuner and V_{max0} in Fig.10. The experimental result was compared with the calculated reduction rate, which could be read out along the dashed line in Fig.14. The calculated ratio of V_{max}/V_{max0} was changed from 1.0 to 0.34 by shortening the pre-matching stub tuner length, A_P from 0.25 to 0.052. The calculated RF voltage reduction rate was plotted by a solid line in Fig.11. The measured value agreed with the calculated one.

4.2 Multipactoring discharge

As described in the sections about aging procedure (Sec.3.1) and about vacuum pressure increase during long pulse operation (Sec.3.3), the multipactoring discharge caused the vacuum pressure increase, which has been researched for forty years. The multipactoring discharge occurred at the position of a low RF voltage,

e.g. several hundred V. The range of the RF voltage inducing the multipactoring discharge depends on the product of an applied frequency, f and a space distance of coaxial electrodes, d [21]. In the series of experiments, the space distance between transmission lines is 7 cm and the product of fd was 320–350 MHzcm. The RF voltage ranges from 260 V to 1.6 kV, which could be read from the contour map of the plane of fd and V_{RF} of the multipactoring discharge. The transmission line and the RF antenna were inspected after the long pulse test of the transmission system. The position of multipactoring discharge could be identified by the surface characteristics on the transmission line, which became smooth and glossy at that location. The trace position was at 2.9 m from the end of the RF antenna, which agreed with the position at the minimum RF voltage as shown in Figs.9 and 10.

The multipactoring discharge was confirmed by mean of another phenomenon. When the impedance matching was carried out at a low power level, the mismatching was observed at the applied RF power higher than 7 W and the vacuum pressure increased consequently. The maximal RF voltage was deduced to be $V_{RF} = 300$ V by taking into account the loading resistance, 0.4Ω . The figure of $V_{RF} = 300$ V agreed fairly well with the lower RF voltage inducing the multipactoring discharge, i.e. 260 V. There seemed to be a difference between 260 V and the experimental value, 300 V; however, the observed value of 300 V agrees with the RF voltage of 296 V, which is obtained after 2 minutes of outgassing [21].

In the series of experiments, the RF loading resistance was 0.4Ω . The voltage reflection coefficient was 0.984 and the voltage standing wave ratio (VSWR) was 125. As RF voltage was applied in the range from 60 kV to 30 kV, there always existed the RF voltage causing the multipactoring discharge. On the other hand, the RF loading resistance will be expected to be 5Ω at the ICRF heating experiment on LHD and VSWR will be 10. Even when the applied RF voltage is as low as 20 kV, the RF voltage of the minimum exceeds the higher threshold of the RF voltage, 1 kV for the multipactoring discharge.

5. Conclusion

Steady state ICRF heating technologies have been developed at the National Institute for Fusion Science. The transmission system withstood $V_{RF} = 58$ kV for 10 seconds and 40 kV for 30 minutes, which were equivalent to the capability of the RF transmission

power, 3.4 MW and 1.6 MW with a plasma loading resistance, $5\ \Omega$. The developed RF components were qualified for steady state operation at high RF power; these were the transmission line of 240 mm ϕ , the liquid stub tuner, the ceramic feed-through and the RF antenna. In addition, the effectiveness of the pre-matching stub tuner was demonstrated in reducing the RF voltage to one third, which leads to a higher RF heating efficiency. Furthermore the procedure for aging the RF antenna was proposed. Antenna aging was quickly achieved by properly selecting the repetition rate, RF pulse length and RF voltage.

These technological developments should be important in achieving a high RF power heating or current drive with the steady state operation in LHD and future devices such as ITER.

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