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Hardware of Steady State ICRF Heating for LHD

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Abstract

One of the engineering targets of ion cyclotron range of frequency (ICRF) heating for LHD is to operate in high power (up to 12 MW) and steady state (30 minutes). Research and development of ICRF heating system for steady state operation have been carried out in several years. ICRF system consists of a variety of components such as transmitter, coaxial transmission line, DC break, impedance matching tuner, ceramic feedthrough and antenna. All of these components are designed, fabricated and tested for steady state operation. We concluded that these components were available for steady state experiment in LHD. We have injected the ICRF power into plasma during more than one minute so far.

Keywords:

ICRF heating, LHD, steady state heating

1. Introduction

The plasma experiments on the Large Helical Device (LHD) have started in 1998 and the three series of experimental campaign have finished up to 1999 [1,2]. Steady state operation is one of the features of LHD and ion cyclotron range of frequency (ICRF) heating system has been developed to achieve the steady state heating.

Developed ICRF heating system consists of various kinds of components such as transmitter, dummy load, coaxial transmission line, DC break, impedance matching tuner, ceramic feedthrough and antenna. A lot of experiments have been done for many years [3-8]. We pick up some components and summarize the results of R & D experiments in this paper.

2. R & D Experiments of Transmitter

Development of transmitter has been done using a huge steady state dummy load, which used 96 of water-cooled ceramic resisters [3]. The transmitter was designed and constructed to cover very wide frequency range (25 - 100 MHz) and launch high power in steady state operation. Cavity of final power amplifier is double coaxial shape and two stubs are used to acquire the impedance matching for output power. Allowable power reflection coefficients are 0.59, 0.47, 0.36, and 0.26 for the output power of 0.5, 1.0, 1.5, and 2.0 MW, respectively.

Figure 1 shows the time history of 5000 seconds operation. The frequency is 50 MHz. RF power, temperature of inner transmission line and ion pump current of tetrode tube are plotted [4]. There were two factors that led to success in the high power steady state operation of transmitter. One is reinforcement of cooling and the other is operation in low impedance mode. We could enlarge the operation time more than 100 seconds after we increased the air cooling to the double coaxial cavity and ferrite at the final power amplifier. The low impedance mode operation was the most important to achieve the high power in steady state operation. We operated in the condition of large cathode current, large

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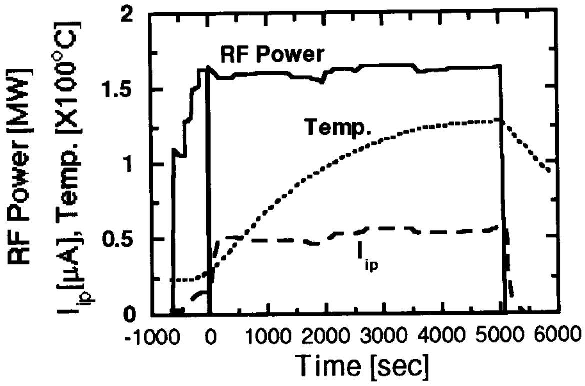

Fig. 1 Demonstration of the steady state operation.

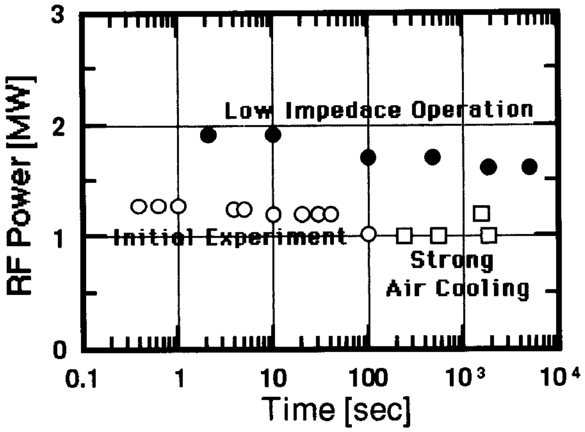

Fig. 2 Expansion of RF output power and duration time of the transmitter.

efficiency and small ion pump current. The ion pump current is proportional to the vacuum pressure in the tetrode tube. As the pressure in the tetrode increases, arcing occurs in the tube. Evolution processes of the RF power and pulse length are summarized in Fig. 2.

3. R & D Experiments of RF Components

3.1 Experimental setup

The experiments have been carried out at the ICRF test stand as shown in Fig. 3 [5,6]. It consists of transmitter, dummy load, coaxial transmission line, coaxial switch, DC break, impedance matching tuner, ceramic feedthrough, test loop antenna and vacuum chamber. In unmatched section between liquid stub tuner and antenna, there is no dummy load and circuit resistance is low. Then, VSWR in this section is very large. We estimated peak voltage of the transmission line by the following equation:

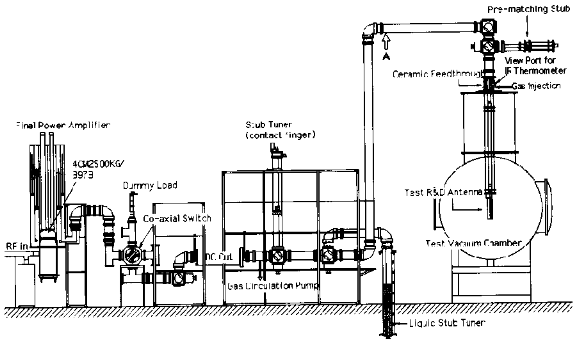

Fig. 3 Layout of ICRF test stand for R & D experiments of RF components.

$$V_{max} = (Z_0 \times \rho \times (RFpower))^{0.5},$$

where Z_0 and ρ are the characteristic impedance and the VSWR of the transmission line, respectively. When we tested feedthrough, the pre-matching stub was used to reduce the voltage of transmission line. When the transmission line was tested, it was terminated at point A in Fig. 3.

3.2 Liquid stub tuner

We used conventional stub for the impedance matching circuit at the test stand in the beginning of the experiment. However, the contact finger was broken in long pulse operation . Then, we have developed the stub using the dielectric liquid without contact fingers [7]. Schematic drawing of liquid stub tuner is shown in Fig. 4. Silicon oil is introduced between inner and outer conductors. The difference of RF wavelengths in liquid and insulation gas is used for the impedance matching. The relative dielectric constant of the oil is 2.72 and dielectric loss tangent tanδ is 10^{-4} at 10 MHz. The vapor pressure is less than 0.1 Torr at 240°C. Using our test stand, maximum RF voltage of 50 kV was applied for 30 minutes at the liquid stub tuner. The increase of liquid temperature was less than 50°C by water cooling flowing inside the inner conductor. We could change the position of liquid surface during operation to reduce the reflected power without any problem.

3.3 Feedthrough

We tried to test the several types of feedthrough to find out which type was appropriate for steady state operation [6]. Figure 5 shows the drawing of the tested feedthroughs. The ceramics is aluminum except for cylindrical type, which uses silicon nitride composite

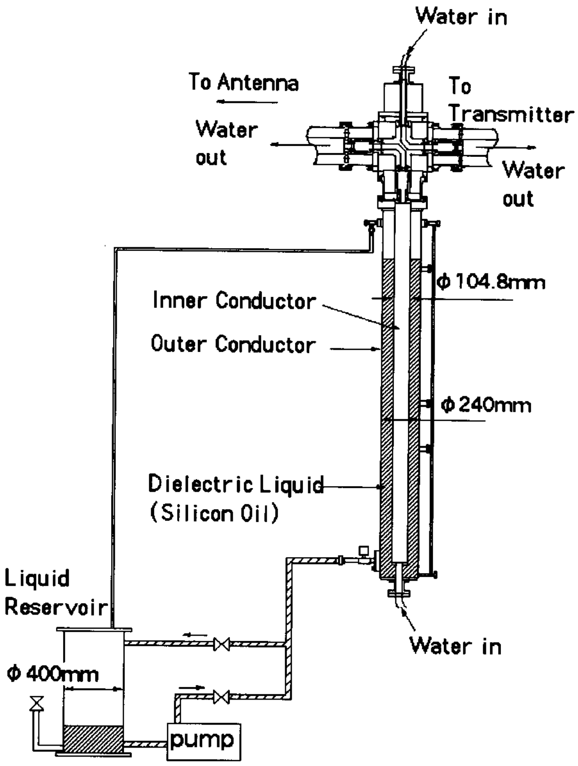

Fig. 4 Schematic drawing of liquid stub tuner.

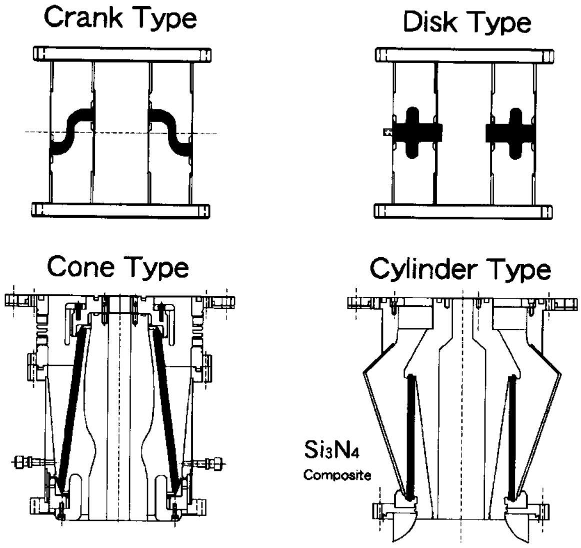

Fig. 5 Cross section of tested feedthroughs. Ceramic part is painted over with black.

ceramics and O-ring vacuum seal without brazed seal. The feedthroughs which used crank and disk shape of ceramics were broken more than 30 kV in several minutes' operation. Vacuum leak occurred at the brazed point between the ceramic and Kovar alloy. The estimated dissipated power was the maximum at this leak point. Higher RF voltage of the order of 40 kV was achieved for 30 minutes operation for cone and cylinder types. Further experiment was impossible because the pressure rise in the test chamber. The increase of ceramic temperature in 30 kV and 30 minutes operation was less than 40°C. When gas cooling was applied at the ceramics, it was reduced to about 10°C and saturated in 20 minutes. We have selected cone type feedthrough for LHD ICRF system.

3.4 Loop antenna and transmission line

R & D antenna has been fabricated and tested to establish the technology for steady state operation [3,8]. The antenna is 380 mm wide and 600 mm long and simulated the antenna that is installed from upper port. Inner conductor, backplate and Faraday shields were cooled by water. One of the main subjects was the heat removal from the carbon protectors at the side of the antenna. When we injected an RF power of 500 kW (assumed plasma loading resistance of 5 Ω), the temperature of the carbon protectors increased rapidly and saturated at higher than 120°C in around 10 minutes. This temperature was much higher than that of the other parts except for the edge of the Faraday shield, where the measurement might be uncertain. The heat source is thought to be induction current by the antenna RF current. In consequence of the experiments, we decided to insert carbon sheet between the carbon protector and the supporting copper plate. The antenna was tested together with feedthrough and RF voltage of 40 kV was achieved in 30 minutes operation.

The antenna is fed by coaxial transmission line which diameter is 240 mm to avoid the RF breakdown. The characteristic impedance is 50 Ω. Cooling water flows inside of the transmission line like other components. We developed special connector of inner conductor, which has O-ring for water seal and contact fingers for electric contact. We also made T- and L-junction with inlet and outlet of cooling water. The transmission line had no problem with 50 kV and 30 minutes operation [5,6].

4. Steady State Operation in LHD

First trial of steady state operation using ICRF heating was conducted in LHD in end of 1999. ICRF power of about 700 kW was applied to the plasma for 68 seconds as shown in Fig. 6. We injected moderate

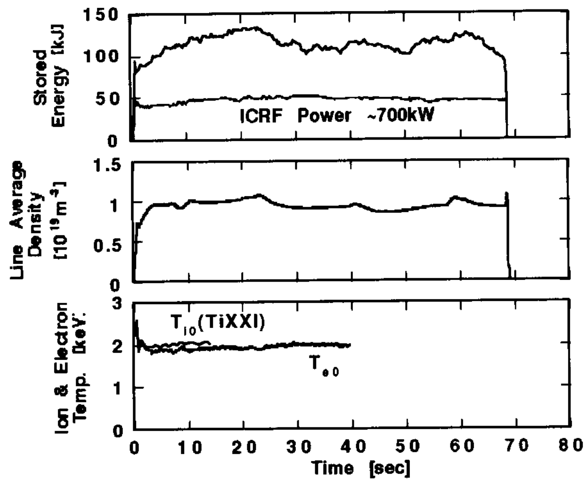

Fig. 6 Time evolution of plasma parameters during 68 seconds operation.

power because we could not use the well-conditioned tetrode tube for steady state operation, which had trouble in the former experiment. The transmitter determined the pulse length because adjustment and conditioning of the transmitter for steady state operation was not enough. The plasma which has the stored energy of more than 100 kJ and ion and electron temperatures of 2 keV is sustained more than one minute by ICRF heating alone. RF power and duration time will be increased much more if we take a lot of time to optimize the transmitter.

5. Summary

We have developed steady state ICRF system for LHD. The result is summarized as follows.

Transmitter	1.6 MW, 5000 seconds
Liquid Stub Tuner	50 kV, 30 minutes
Feedthrough	40 kV, 30 minutes
Loop Antenna	40 kV, 30 minutes
Transmission Line	50 kV, 30 minutes

We have injected ICRF power of about 700 kW for more than one minute. We expect to enlarge the pulse length and increase the RF power much more in future experiment.

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