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ICRF Heating Experiment on the Large Helical Device

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Introduction

The Large Helical Device (LHD) is the largest superconducting helical device. The major and minor radii of the plasma are 3.6-3.9 m and 0.6-0.65 m, respectively. LHD has a capability of steady state operation by the superconducting coil system and helical magnetic configuration. Ion cyclotron range of frequency (ICRF) heating is one of the heating methods for LHD and the system has been developed for high power and steady state heating experiment [1,2].

The ICRF heating experiment has started preliminarily in the 2nd cycle experimental campaign in 1998 [3,4]. Since the magnetic field strength was 1.5 T, the wave frequency was selected to 25.6 MHz, which was lower boundary of the frequency range of the system. In the experiment, a maximum 300 kW of ICRF power was injected for 0.2 seconds. The density was so low that the plasma loading resistance was also low. The plasma stored energy increased from 13 kJ to 26 kJ, which was almost the same heating efficiency as that of electron cyclotron heating (ECH).

In the 3rd cycle experimental campaign, we made several modifications in the ICRF system and LHD from the 2nd cycle. The magnetic field strength was increased to 2.75 T. Thus, the wave frequency was also increased to 38.47 MHz. Optimization of the ICRF heating became possible by moving the position of the ion cyclotron resonance layer by changing the magnetic field strength. The radiation loss power was decreased by the use of Titanium gettering. The density attained in the ICRF heating experiment was extended to higher region. We adopted an inward shifted magnetic axis configuration in order to reduce the deviation of deeply trapped ion orbit from the mod-B surface. In this paper, results of the ICRF heating experiment from the 3rd cycle are described.

Experimental Setup

The experiment was carried out using a pair of loop antennas as shown in Figure 1. The antennas are installed from the upper and lower ports of LHD and located at the higher magnetic field side on the outside of the torus. Here, the length, width, and depth of each antenna are

0.6 m, 0.46 m, and 0.17 m, respectively. The surface of antenna is twisted to fit the shape of the plasma boundary. Faraday shield with a single layer is lined on a parallel with the line of magnetic force. Carbon protector is installed on the both side of the antenna. Antenna strap, Faraday shield and back plate have cooling channel for long pulse operation. The antenna position is movable in radial direction by 0.15 m. Each antenna is fed by the separate transmitter, which was developed for steady state operation [5]. All the RF components of transmission line, DC break, liquid stub tuner and feedthrough are cooled by water for steady state operation.

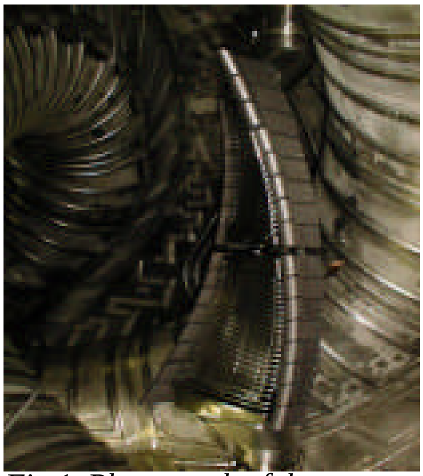

Fig.1. Photograph of the antenna installed in LHD.

Configuration of Resonance Layers

Position of the ion cyclotron (IC) resonance layer and the two-ion hybrid resonance (mode conversion: MC) layer is important for efficient ICRF heating. We tried several configurations of the resonance layers in order to optimize the ICRF heating condition. Figure 2 shows a typical configuration, in which the ICRF heating experiment was mainly carried out. In this calculation, magnetic field strength is 2.75 T and the wave frequency is 38.47 MHz. The working gas is helium and 30 % of hydrogen is mixed as a minority species. The central electron density is 1×10^{19} m^{-3}. IC resonance layer is split vertically and MC layer is located near the magnetic axis. Position of the MC layer becomes away from that of the IC layer when the minority ratio increases. Fast wave launched from the antenna is absorbed at the IC layer and ions are heated. Electron heating occurs by ion Bernstein wave mode-converted at the MC layer. These two heating mechanisms exist as competitive relation.

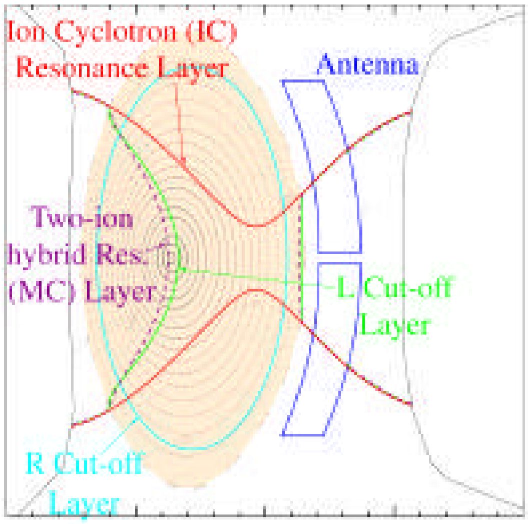

Fig.2. Position of the resonance and cut-off layers at the plasma cross section.

Experimental Results

At first, we investigated the optimal heating condition changing the magnetic field strength and the wave frequency. The results are summarized in the figure 3. The plasma absorption power was obtained from the decay of the plasma stored energy at the time of turn-off of the RF pulse. In this experiment, position of the IC layer is changed from the horizontally split configuration to the vertical split configuration as shown in the figure 3. In each heating configuration, the heating efficiency was measured in a wide range depending on the minority hydrogen ion concentration. The highest heating efficiency is obtained when the IC layer is located near the saddle point of the magnetic field. The experiments are carried out in this configuration; the magnetic field strength is 2.75 T and the wave frequency is 38.47 MHz.

The ICRF sustained plasma with almost 200 kJ of the stored energy at 1.8×10^{19} m^{-3} of the line averaged electron density was achieved by the injection of 1.2 MW of the ICRF heating power, which is drastically improved from the 2nd cycle experiment. The central electron temperature is 1.7 keV and the radiation loss power is 300-400 kW. Figure 4 shows the ion energy distribution at the perpendicular pitch angle observed by the natural diamond detector [6]. The ICRF power is injected from 0.5 seconds to 5.1 seconds in this discharge. The high energy ion tail is generated by injection of the ICRF heating power. The energy of the tail reaches more than 200 keV.

The ICRF power was also applied to the NBI heated plasma. In the typical discharge, port through power and the energy of the beam is 1.45 MW and 130 keV. The stored energy was increased from 230 kJ to 340 kJ with the injection of 1.3 MW of the ICRF heating power. The line averaged electron density was 2×10^{19} m^{-3}. From evaluation of the heating performance using International Stellarator Scaling 95, it is found that the ICRF heating is comparable with the NBI heating. The ICRF plasma was also used for the target plasma for the NBI heating in another series of experiments.

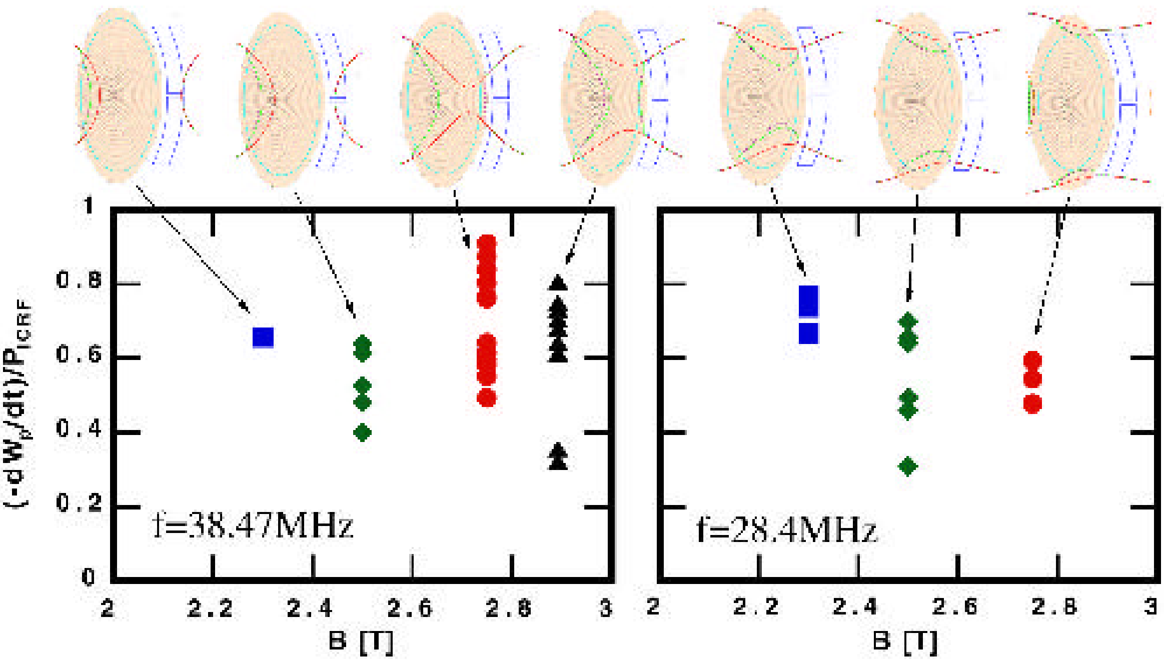

Fig.3. ICRF heating efficiency in various position of the IC layer.

The long pulse discharge was demonstrated by using the ICRF heating power. Figure 5 shows the time evolution of the plasma parameters in the longest discharge sustained by the ICRF heating only. ICRF power of 0.7 MW was injected into the plasma and the stored energy more than 100 kJ was maintained for 68 seconds. The density was controlled manually to be kept at 1×10^{19} m^{-3}. The central electron and ion temperatures were about 2 keV. The radiation loss power was almost constant during the discharge. Line intensity of OV and FeXVI was also kept constant. Almost all plasma parameters behaved constant more than one minute. The reflected ICRF power is increased gradually during the operation. Real time control of the impedance matching, which has been already tested successfully by using the liquid stub tuner, will be necessary for longer operation. It is expected to sustain the plasma much longer by the ICRF heating alone.

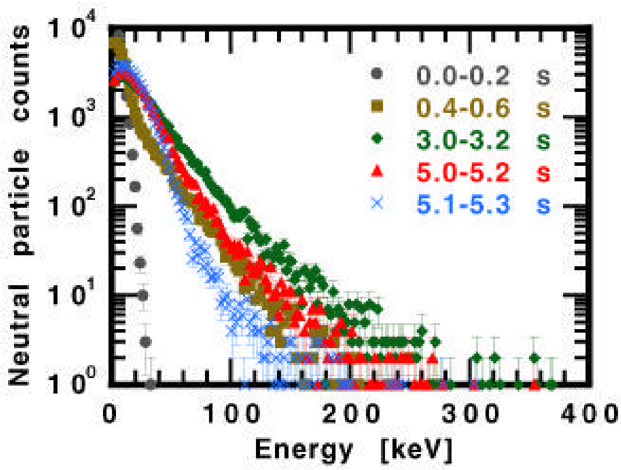

Fig.4. Energy distribution of the neutral particle counts plotted at the different five times ranges.

In the long pulse experiment, it is preferable to move away the antenna from the plasma. We examined the antenna coupling in changing the antenna position. Figure 6 shows the loading resistance as a function of the antenna distance to the plasma. The electron density is 3×10^{19} m^{-3}. The loading resistance of 5 Ω is obtained even if the antenna is located at the 10 cm away from the plasma. The result was compared with the calculation using the resistance code [7], which was developed based on the Theihaber's analysis [8]. One-dimensional slab geometry of the plasma is assumed. As shown in the Fig.6, the calculation result agrees with the experimental result very much.

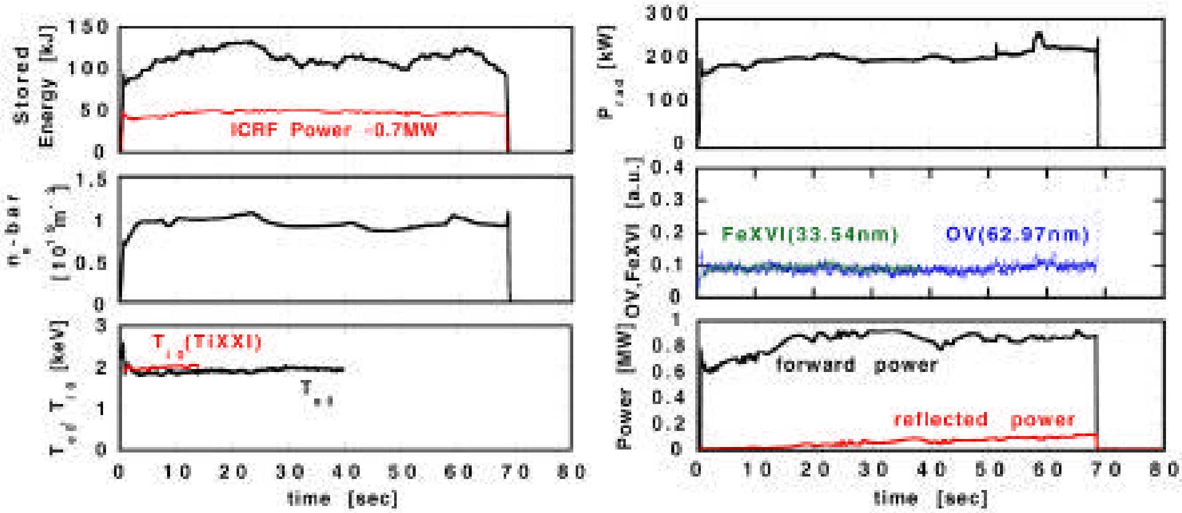

Fig.5. Time evolution of plasma parameters in the long pulse ICRF-sustained plasma.

Summary

ICRF heating experiments on LHD have been carried out successfully, though it is difficult to get good results from ICRF heating on the helical / stellarator device. High heating efficiency was obtained when the ion cyclotron resonance layer was located near the saddle point of the magnetic field. Ion heating mainly occurred in this case. The confinement characteristic of ICRF heating was almost the same as that of NBI heating. The long pulse discharge more than one minute was also demonstrated by using the ICRF heating only. Dependence of antenna loading resistance was calculated to compare with the experimental data. They agreed well and the loading resistance of 5Ω was obtained even if the antenna was located 10 cm away from the plasma. In the next cycle experiment, another two pairs of the antenna will be installed and the experiment using the higher ICRF power will be possible.

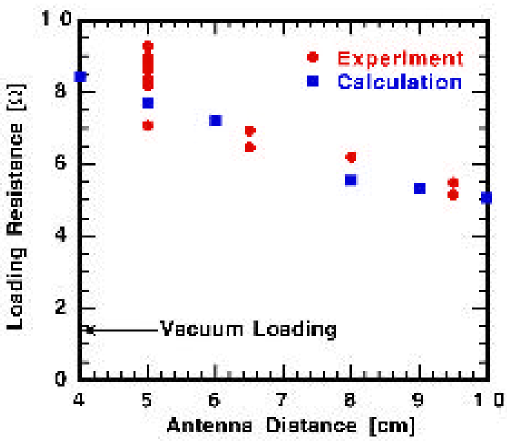

Fig.6. Dependence of loading resistance on the antenna distance.

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