Electron Heating by ICRF Mode-Conversion Heating in LHD

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Electron heating regime using with radio-frequency waves in the ion cyclotron range of frequencies (ICRF) has been investigated in helical magnetic configuration. Mode-conversion scenario was applied to the LHD plasmas. When the wave frequency is change to be lower than that in the standard ICRF heating (minority ion heating) condition, the resonance layers are moved away to the peripheral region of plasma. Two-ion hybrid resonance (mode-conversion) layers still locate inside of plasma and fast waves launched by the ICRF antenna are converted to the ion Bernstein waves at these layers. The plasma is successfully sustained by mode-conversion heating only. The measured high-energy ion component shows no ion tail, which is observed in the minority ion heating case. Position of mode-conversion layer is closely related with the ratio of hydrogen ions to helium ions. Hydrogen ice pellet injection was tested to supply the hydrogen ions in the plasma core region. The plasma, which collapsed without the repetitive ice pellet injection was sustained during mode-conversion heating assisted by the repetitive pellet injection. Feasibility of steady state operation using mode-conversion heating is assessed. The plasma duration more than 80 sec. is achieved so far. The experimental result was compared by using 1D full wave simulation code. The electron absorption profile was slightly different when the hydrogen ion ratio was changed.

Keywords: ICRF heating, mode-conversion heating, helical plasma, steady state operation, LHD

1. Introduction

There are many plasma heating modes in the ion cyclotron range of frequencies (ICRF) heating scheme. Mode-conversion heating (MCH) [1] is one of the promising heating modes. MCH was studied with the object of establishing as an effective heating method in a helical configuration. Minority ion heating (MIH) mode has been established as a standard ICRF heating mode [2] in LHD [3]. MIH is mainly used for high power heating experiment and steady state operation [4] for extending the plasma parameters such as density, temperature and duration time in the ICRF-heated plasma by ion heating. However, problems thought to be caused by the high-energy ions accelerated by MIH occurred and were especially severe in steady state operation. Exploring feasibility for applying to long pulse operation is another important purpose to research the MCH.

2. Experimental Setup

In LHD, the existing fast wave antennas, which were used for the MIH experiment were also utilized for the MCH experiment. The wave frequency of 28.4 MHz and the magnetic field strength of 2.75 T were selected. Helium and hydrogen mixture was used as a working gas. Figure 1 shows the location of the resonance layers in the plasma poloidal-cross section for the MCH experiment in LHD. Ion cyclotron resonance layers are located at the

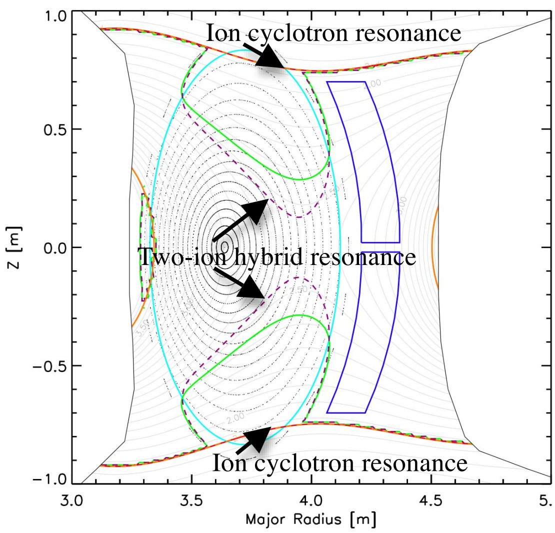

Fig.1 Location of resonance layers in the plasma poloidal-cross section for the mode-conversion heating.

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plasma peripheral region. Wave coupling with ions at the cyclotron layer is estimated to be weak. Electron heating is expected by the ion Bernstein waves mode-converted from the launched fast waves theoretically. Position of mode-conversion layers (two-ion hybrid resonance layers) is related to the hydrogen ion ratio to the helium ions. As the hydrogen ratio increases, mode-conversion layers move inside of the plasma. High hydrogen ion ratio will be required to heat the plasma core region as assumed in the Fig. 1 ($n_H/(n_H+n_{He})=0.65$).

3. Experimental Results

Fundamental heating mechanism of MCH was studied by the 10 sec. discharge. The ICRF power was injected to the NBI target plasma as shown in Fig. 2. The NBI power was 4.5 MW. The plasma was sustained during the ICRF power injection. The plasma stored energy was kept during the ICRF pulse and decreased at the same time as the RF turn-off. The line-averaged electron density was 0.7×10^{19} m^{-3} and the central electron temperature was 0.6 keV. The radiation loss power was kept constant during the ICRF injection. The high-energy ion tail, which was generated by the MIH was not observed by measurement of fast neutral analyzer as shown in Fig. 3. The electron temperature profile was broad and there were small peaks near the location of the mode-conversion layer as shown in Fig. 4. The experimental result shows that the plasma is sustained by the electron heating.

It was experimentally verified that control of the hydrogen ion ratio was important in MCH. In Fig. 5,

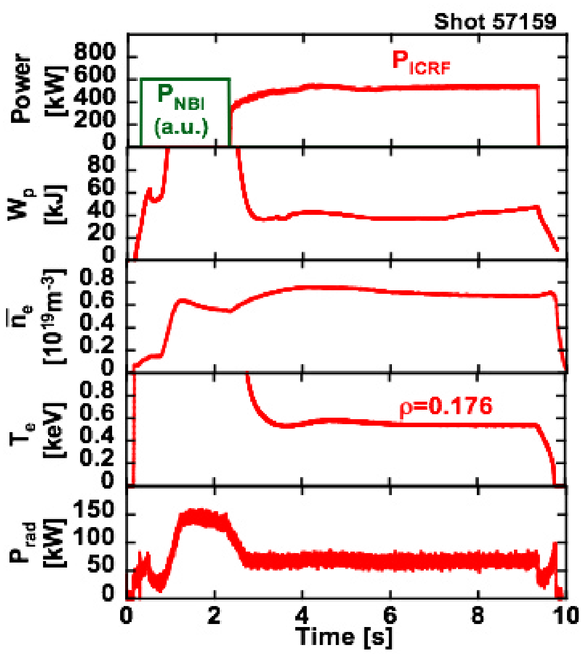

Fig.2 Time evolution of ICRF power, plasma stored energy, line-averaged electron density, electron temperature, and radiation loss power.

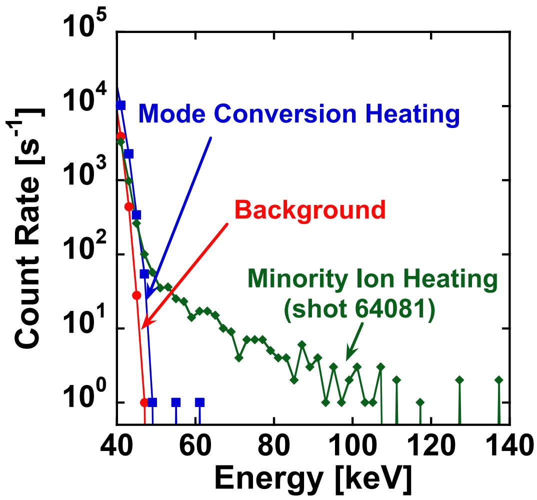

Fig.3 Energy spectrum of high-energy ions measured by FNA.

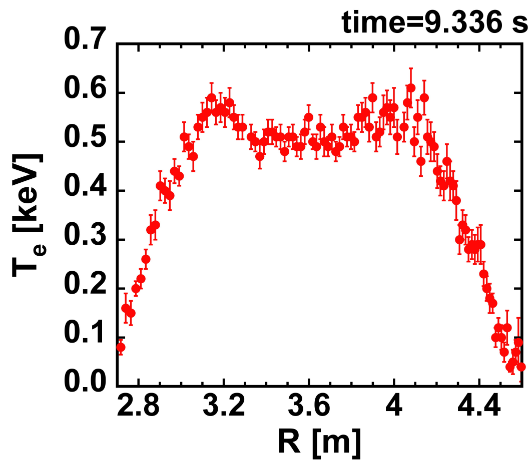

Fig.4 Electron temperature profile during mode-conversion heating at 9.336 sec.

repetitive hydrogen pellet injection was used to supply the hydrogen ions. In these experiment, the plasma was not sustained during the ICRF pulse without the repetitive pellet injection. The plasma maintained during the ICRF pulse with the repetitive pellet injection. The hydrogen ratio measured by a spectroscopy increased about 20 % with the repetitive pellet injection. However, it reflects the plasma surface region. The hydrogen ratio at the inside of the plasma is more important but it was not measured. The ICRF power responded to and was increased by the injection of the pellet. The radiation loss power was smaller in the pellet injection case. Greatly different from the MIH case, high ratio of hydrogen ion was needed to heat the plasma core region and sustain the plasma.

There is a density limit in the ICRF sustained plasma. The limit may be different in the MCH and MIH. Figure 6 shows the achieved line averaged electron density as a

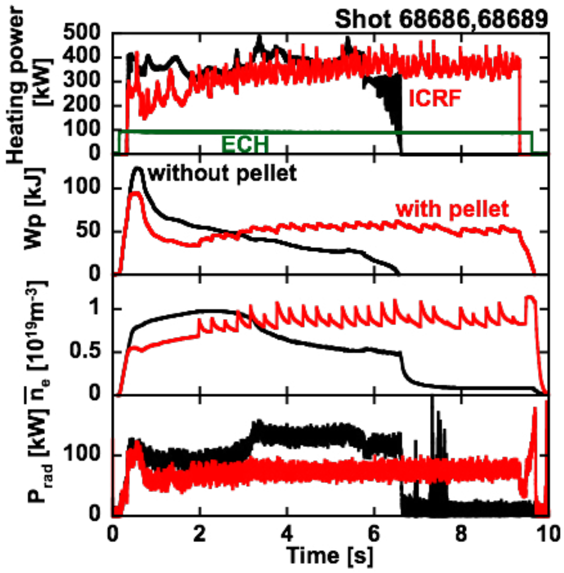

Fig.5 Comparison of time evolution of plasma parameters with and without repetitive hydrogen pellet injection.

function of the injected ICRF power. High power injection was not conducted in the MCH case. Higher density plasma was sustained in MCH at the same heating power. Higher density operation will be easier in the MCH case than in the MIH case. This difference may be attributed to the difference of heating regime, electron heating or ion heating.

Difficulty of MCH was that the observed plasma loading resistance was small. Relation between the plasma loading resistance and the line-averaged electron density was studied as shown in Fig. 7. Data of the high-density region was taken with assist of the NBI heating. The injected ICRF power is about 350 kW per antenna in these discharges. The loading resistance in the discharge of Fig. 2 (labeled as “7 sec discharge” in Fig.7) was 1.7 Ohm, which is a half of the MIH case in the same

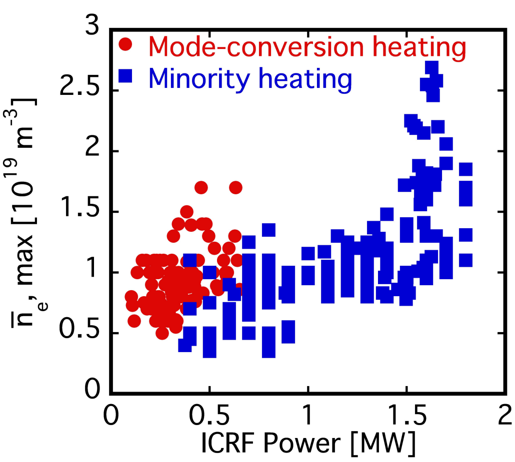

Fig.6 Achieved line-averaged electron density as a function of the injected ICRF power.

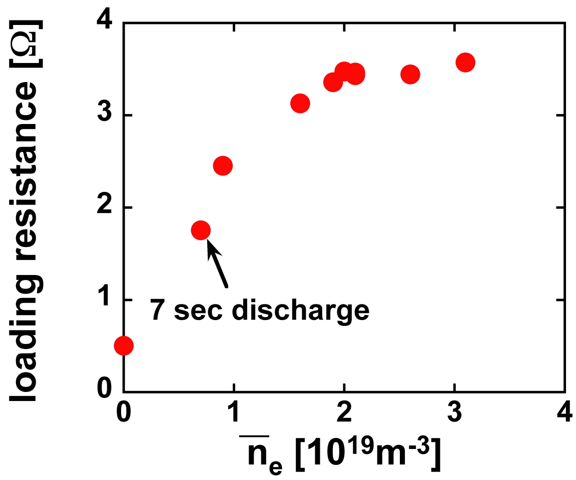

Fig.7 Plasma loading resistance as a function of the line-averaged electron density.

density region. Then, voltage of the coaxial line is higher than that in the MIH case for the injection of the same heating power. Increase of the plasma loading resistance by higher density operation is required so as to inject the higher power. If the density is raised to 2×10^{19} m^{-3} in the MCH case, almost the same heating power will be injected in the MIH case at the density of 0.7×10^{19} m^{-3}.

MCH was applied to long pulse operation. The plasma discharge more than one minute was achieved so far. Figure 8 shows time evolution of plasma parameters in one of the long pulse discharges. ECH is also used for assist of the discharge and repetitive hydrogen pellet injection was started from about 38 sec. The ICRF power was reduced sometimes by voltage interlock of the transmission line and the electron density and temperature responded to the change of the heating power. The plasma was terminated by abrupt density increase. Sparks and influx of metallic impurity, which occurred in the long pulse operation by the case of MIH were not observed. Pattern of temperature increase at divertor plates was different from the MIH case. Temperature increase was large near the ICRF antennas in the MIH case while there was no such peak in the MCH case. This difference is thought caused by the difference of electron heating and ion heating.

4. Full Wave Calculation

Full wave calculation in one-dimensional slab plasma model has been conducted in preliminary. The advantage of the code, W1 [5], is that it introduces mode-converted ion Bernstein wave in addition to launched fast wave. The helical magnetic configuration is included through helical ripple, EPSH as follows:

$$B(x) = R/(R+x) + EPSH * \rho^2$$

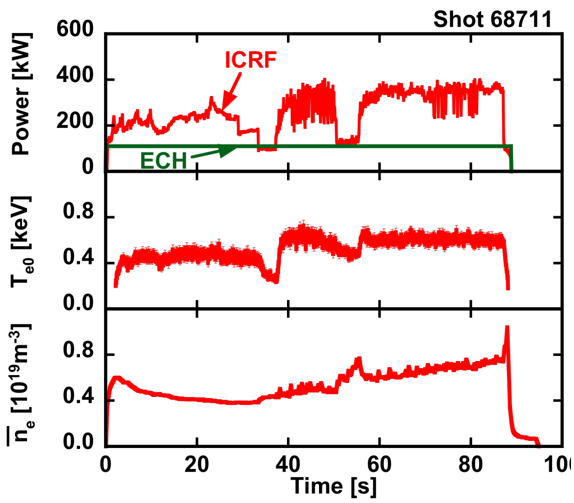

Fig.8 Time evolution of RF power, electron temperature, and line-averaged electron density when MCH is applied to the long pulse operation.

,where R is a major radius and x is minor radius direction, and ρ is a normalized minor radius. The relation between the magnetic field configuration and the flux surface is different from the actual device. The wave is launched from the high-field side and assumed to move as shown in Fig. 9. The density and temperature profiles are assumed as quartic and parabolic, respectively. It was assumed that the central electron density is 0.8x10^{19} m^{-3}, the central electron and ion temperatures are 0.6 and 0.4 keV, respectively. Two different hydrogen ion ratio of 30 % and 50 % was compared in the calculation as shown in Fig. 10. Almost all of the heating power was absorbed by electrons in both the cases. The profile of the electron absorption is different in the two hydrogen ratio. The electron absorption near the mode-conversion layer is stronger in the 50% case. Further analysis is required to discuss about wave behavior and absorption profile in cooperation with three-dimensional full wave codes.

5. Conclusion

Mode-conversion heating was investigated in LHD and feasibility of steady state operation using MCH was verified experimentally. No high-energy ion tail was observed as expectedly. The plasma was thought sustained by the electron heating by mode-converted ion Bernstein wave. Hydrogen ion ratio was important for effective heating. Fueling of hydrogen ions by repetitive pellet injection was tested and turned out to be effective. Higher density operation is needed to inject the higher power. Favorable result was obtained in the preliminary long pulse operation. Full wave calculation using one-dimensional code has just started. Slightly different electron absorption profile was obtained in changing the hydrogen ion ratio. Further experiment of higher power and longer pulse operation using the MCH is planed near future.

Acknowledgement

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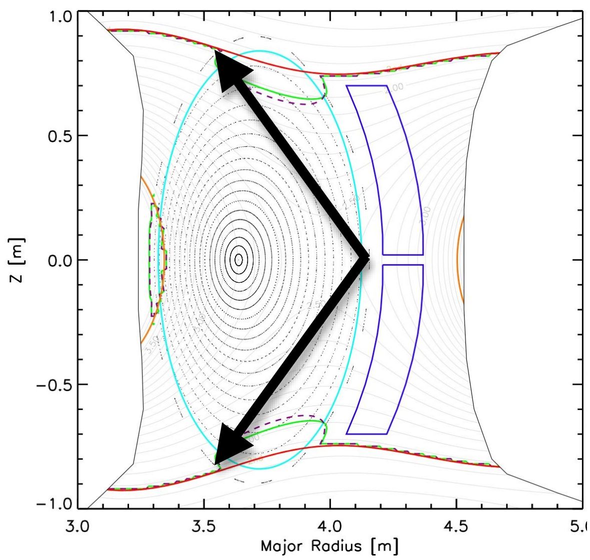

Fig.9 Assumed movement of launched wave in one-dimensional full wave calculation. Hydrogen ion ratio is 30 %.

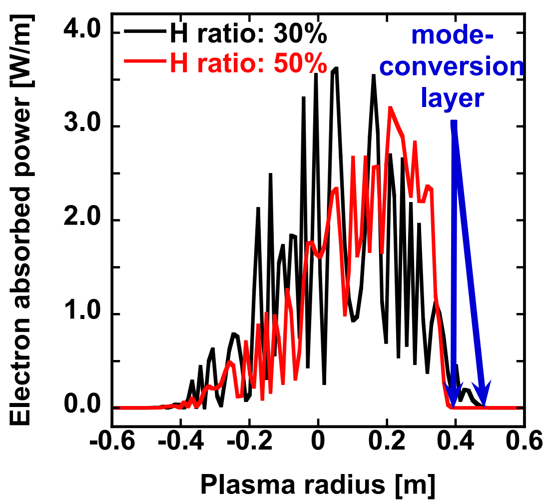

Fig.10 Electron absorption profile calculated by one-dimensional full wave code. Location of the mode-conversion layers are also indicated for the two cases.