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# ICRF mode-conversion heating and its application to long pulse discharge in LHD

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Mode-conversion heating (MCH) [1] is one of the attractive heating modes in ion cyclotron range of frequencies (ICRF) heating scheme. MCH was investigated aiming at establishing as an effective heating method in a helical configuration. Minority ion heating (MIH) has been established as a standard ICRF heating mode [2] in LHD [3]. It is mainly used for high power heating experiment and steady state operation [4] for extending the plasma parameters by ion heating. However, problems thought to be caused by the high-energy ions accelerated by MIH occurs and especially severe in steady state operation. Applying to long pulse discharge experiment is another important purpose to research the MCH.

In LHD, 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 map of resonance layers in poloidal-cross section for MCH experiment in LHD. Ion cyclotron resonance layers are located at plasma peripheral region. Wave coupling with ions at the cyclotron layer will be weak. Electron heating is expected by ion Bernstein waves mode-converted from launched fast waves theoretically. Position of mode-conversion layers (two-ion hybrid resonance layers) is related to hydrogen ion ratio to helium ions. As the hydrogen ratio increases, mode-conversion layers

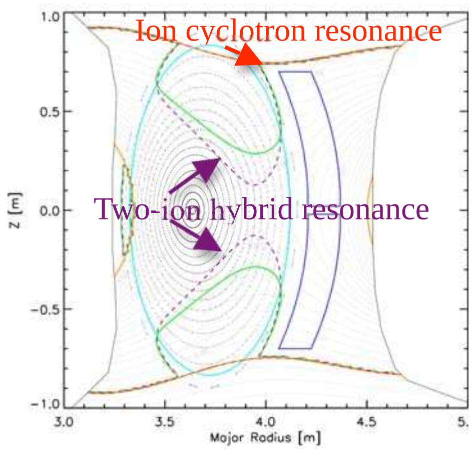


Fig.1 Position of resonance layers in poloidal-cross section for MCH.

moves inside of the plasma. High hydrogen ion ratio will be required to heat the plasma core region as assumed in this figure ($n_H/(n_H+n_{He})=0.65$).

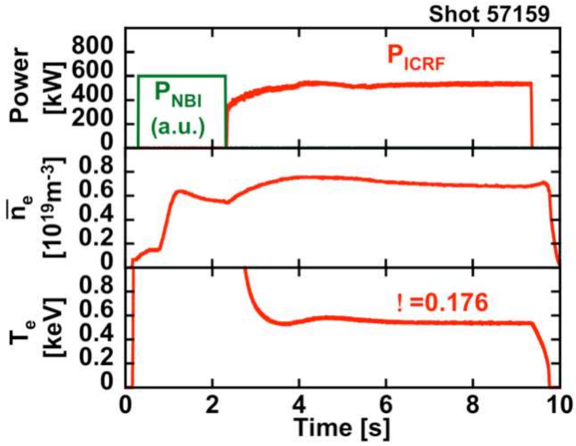


Fig.2 Time evolution of ICRF power, line-averaged electron density, and electron temperature.

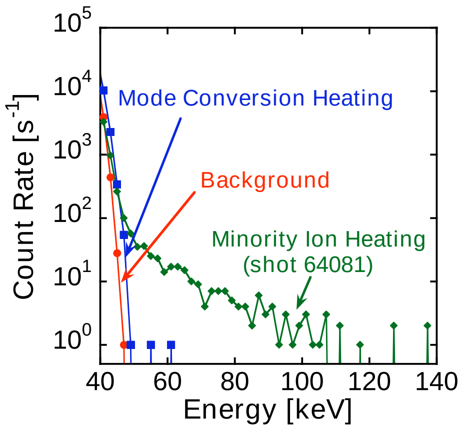


Fig.3 Energy spectrum of high-energy ions measured by FNA.

Essential heating mechanism of MCH was studied by 10 sec. discharge. The ICRF power was injected to NBI target plasma as shown in Fig. 2. The plasma was sustained during the ICRF power injection. The line-averaged electron density was $0.7 \times 10^{19}$ $m^{-3}$ and the central electron temperature was 0.6 keV. The high-energy ion tail, which is generated by the minority heating was not observed by measurement of fast neutral analyzer as shown in Fig. 3.

It was experimentally verified that control of the hydrogen ion ratio was important in MCH. In Fig. 4, 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 ICRF power responds to and increases by the injection of the pellet. Greatly different from MIH, high ratio of hydrogen ion is needed to heat the plasma core region.

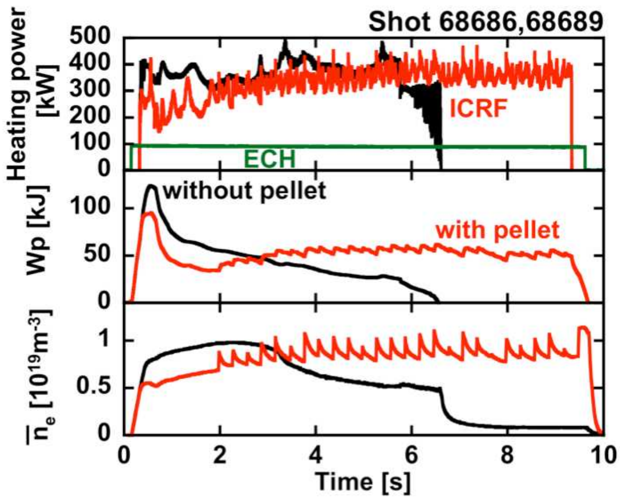


Fig.4 Comparison of time evolution of plasma parameters with and without repetitive hydrogen pellet injection.

Difficulty of MCH was that the observed plasma loading resistance was small. Relation between the plasma loading resistance and line-averaged electron density was studied. Data of high-density region was taken with assist of the NBI heating. The loading resistance in the discharge of Fig. 1 was 1.7 Ohm, which is a half of the MIH case in the same density region. Then, voltage of coaxial line is higher than the MIH case in order to inject the same heating power. Increase of the plasma loading resistance by higher density operation is required for higher power injection. If the density is raised to $2 \times 10^{19}$ m$^{-3}$ in MCH, the same heating power will be injected in MIH in the density of $0.7 \times 10^{19}$ m$^{-3}$.

MCH was applied to long pulse operation. The plasma discharge more than one minute was achieved so far. Figure 5 shows time evolution of plasma parameters in one of the long pulse discharges. ECH is also used for assist the discharge and repetitive hydrogen pellet injection was started from about 38 sec. The ICRF power was reduced sometimes by voltage interlock of transmission line and the electron density and temperature respond to the change of the heating power. The plasma was terminated by abrupt density increase. This is conquerable by conditioning of vacuum vessel and divertor plates by repeating the discharge. Sparks and influx of metallic impurity, which occurred in the long pulse operation by MIH were not observed. Pattern of temperature increase at divertor plates was different from MIH case. Temperature increase was large near the ICRF antennas in MIH case while there was no such peak in MCH case.

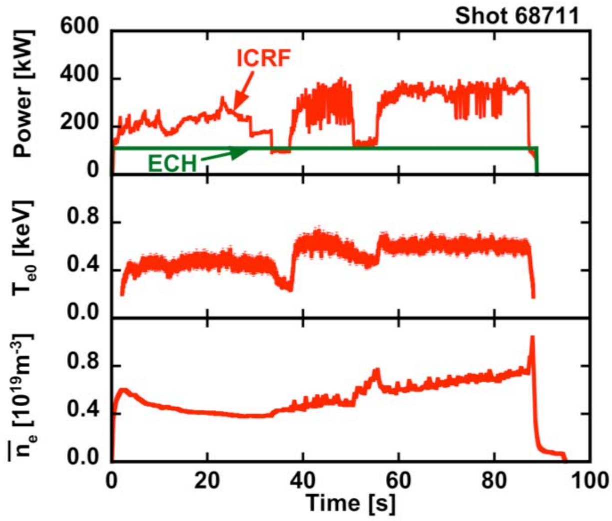


Fig.6 Time evolution of RF power, electron temperature, and line-averaged electron density when MCH is applied to the long pulse operation.

Full wave calculation in one-dimensional slab plasma model has been conducted in preliminary. The strong point 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:

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

,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 high-field side. The density and temperature profiles are assumed as a quartic and parabolic, respectively. It was assumed that the central electron density is $0.8 \times 10^{19}$ $m^{-3}$, 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. 6. Almost all of the heating power was absorbed by electrons in both the cases. Slightly higher power was absorbed in the higher hydrogen ratio. The absorption profile in the 30 % case is broadened from mode-conversion layer. On the other hand, the absorption near the mode-conversion layer is stronger in the 50 % case. Further analysis is required to discuss about wave behaviour and absorption profile in cooperation with three-dimensional codes.

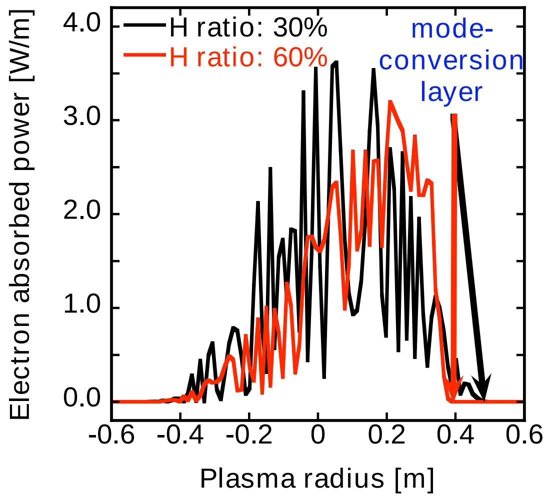


Fig.6 Electron absorption profile calculated by one-dimensional full wave code. Position of mode-conversion layers are also indicated for the two cases.

In summary, MCH was investigated in LHD and feasibility of steady state operation using MCH was verified experimentally. No high-energy ion tail was observed as expectedly. Hydrogen ion ratio was important and supply of hydrogen ion by repetitive pellet injection was tested and turned out to be effective. Further experiment of higher power and longer pulse operation using MCH is planed near future.

Acknowledgement

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