J. Plasma Fusion Res. SERIES, Vol. 6 (2004) 655–657

# Three-Dimensional Calculation Analysis of ICRF Heating in LHD

SEKI Tetsuo, KUMAZAWA Ryuhei, MUTOH Takashi, FUKUYAMA Atsushi[1], SAITO Kenji,
TORII Yuuki[2], TAKEUCHI Norio[2], WATARI Tetsuo, ZHAO Yanping[3] and LHD Experimental Group

*National Institute for Fusion Science, Toki 509-5292, Japan*
*[1]Kyoto University, Kyoto 606-8501, Japan*
*[2]Nagoya University, Nagoya 464-8603, Japan*
*[3]Institute of Plasma Physics Academia Sinica, Hefei 230031, P.R.China*

(Received: 9 December 2003 / Accepted: 1 April 2004)

**Abstract**

Ion cyclotron range of frequencies (ICRF) heating is one of the heating methods for the fusion plasma experiments and also effective for the helical plasmas. For the purpose of analysis of the ICRF heating in the helical plasmas, the three-dimensional full-wave code has been developed. The feature of the helical system compared with the tokamak device is the strong coupling of the toroidal harmonic modes. They cannot be treated independently. Dependence of the power absorption on the position of the ion cyclotron resonance layer is calculated including all toroidal modes. Strong power absorption was obtained when the position of the resonance layer is slightly different from the experimental results. Difference of the position of the resonance layer in different toroidal angle is thought to be important to achieve the good heating efficiency in the ICRF heating for the helical plasmas.

**Keywords:**

ICRF heating, helical device, full-wave code, TASK/WM, three-dimensional calculation

## 1. Introduction

The radio-frequency waves in the ion cyclotron range of frequencies (ICRF) have been used for the plasma heating in the magnetically confined plasmas for many years. In the helical device, it was theoretically predicted that the high-energy ions generated by the ICRF heating would escape from the plasma and the ICRF heating was not effective method for the ion heating. However, in the LHD experiments, they were shown that the ICRF heating was effective in the helical device and the plasma is sustained by the ICRF heating alone more than two minutes [1-4]. To understand the ICRF-heated plasmas and the wave behavior, theoretical analysis using the calculation code is important. In the tokamak plasma, the ICRF heating is well described and understood by using several two-dimensional full-wave codes. In the helical system, the toroidal harmonic modes couple and cannot be treated independently. Displacement of the magnetic field configuration to the magnetic surface in proceeding to the toroidal direction is also very important. Then, the two-dimensional full-wave toroidal codes such as used for the tokamak plasmas are not applicable to the helical plasmas. Therefore, the three-dimensional full-wave code is needed to develop. TASK/WM code is one of the global codes, which calculate three-dimensionally in the helical magnetic configuration.

## 2. TASK/WM Code

To solve the wave excitation, propagation and absorption in the three-dimensional helical plasmas in the ICRF, TASK/WM code has been developed [5]. Modeling of the code was carried out by V.L. Vdovin et al. [6] and it was developed to the calculation code by A. Fukuyama [7]. In a full-wave calculation, the toroidal and the poloidal harmonic expansions are used to solve the wave equation, $\nabla \times \nabla \times \boldsymbol{E} = \frac{\omega^2}{c^2} \overleftrightarrow{\varepsilon} \cdot \boldsymbol{E} + i\omega\mu_0 \boldsymbol{j}_{ext}$, where $E$, $\omega$, $c$, $\overleftrightarrow{\varepsilon}$, $\mu_0$, $\boldsymbol{j}_{ext}$ are wave electric field, wave frequency, light speed, dielectric tensor, magnetic permeability and external antenna current, respectively. Response of the plasma to the electromagnetic wave field is determined by the plasma current and the plasma conductivity tensor. It is expressed as $\boldsymbol{j}_p = \overleftrightarrow{\sigma} \cdot \boldsymbol{E}$. This is included through the plasma dielectric tensor. To solve the equation, the finite Larmor radius expansion that assumes $k_\perp \rho \ll 1$, where $k_\perp$ is the perpendicular wave number and r is the ion Larmor radius, is used. Thus, effect of finite temperature is partially included and the cyclotron damping and the Landau damping are described. However, inclusion of the mode-converted ion Bernstein wave is incomplete. The plasma configuration is given by VMEC MHD equilibrium code [8]. The calculation was carried out in the non-orthogonal flux coordi-

*Corresponding author's e-mail: seki@nifs.ac.jp*

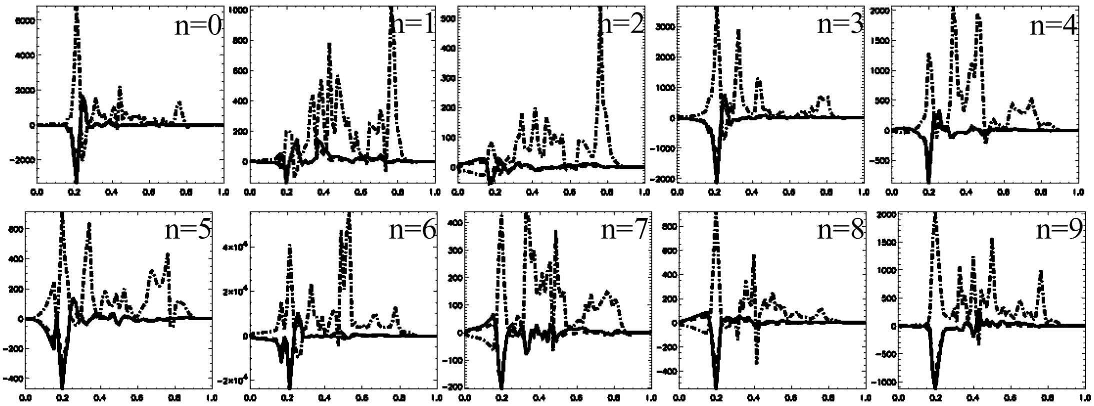


Fig. 1 Radial profile of absorbed power. *n* is toroidal mode number of wave electric field. Solid, broken, and broken-dotted lines are the power absorption by electron, helium, and hydrogen, respectively.

nates ($\psi$, $\theta$, $\varphi$), where $\psi$ is minor radius direction, q is poloidal direction, and j is toroidal direction. The antenna has a single loop in the poloidal direction for exciting the fast wave. The power absorption is expressed as $P = \boldsymbol{E} \cdot \boldsymbol{J}_p$.

Spatial variations of the electric field and the plasma medium are expanded in Fourier series in the toroidal and poloidal directions. Different from the axial symmetric plasmas such as the tokamaks, the toroidal harmonic modes are tightly coupled with each other due to inhomogenity of the helical magnetic configuration in the toroidal direction. The toroidal harmonics are described the condition, $n' = n + kN_h$, where n is the toroidal mode number of the wave electric field, k is harmonic number and $N_h$ is the periodicity of the helical coils. $N_h$ is 10 in LHD. Thus, if the one toroidal mode of the wave electric field is excited by the antenna, the higher toroidal modes will also be excited by coupling simultaneously with it. To include all the toroidal modes of the antenna, one must calculate for the each antenna mode and sum-up the results. Figure 1 shows the radial profiles of the absorbed power in each toroidal mode number n. The magnetic axis position is 3.6 m and the strength of the magnetic field is 2.75 T. The value of the magnetic field is evaluated with the magnetic axis. The central electron density is $1 \times 10^{19}$ m$^{-3}$. The central temperature of ion and electron is 2 keV. The assumed density and the temperature profiles are $n(\psi) = (n_0 - n_s) * (1 - (\psi/\psi_s)^8) + n_s$ and $T(\psi) = (T_0 - T_s) * (1 - (\psi/\psi_s)^2) + T_s$, respectively. The subscripts 0 and s indicate the values at the plasma center and the edge, respectively. The helium plasma with the 10 % of hydrogen is assumed. The wave frequency is 38.47 MHz and the ion cyclotron resonance layers are located at the saddle-point of the magnetic field. In spite of the same plasma parameter and the same position of the resonance layer, the power absorption profile changes with number of the toroidal mode. Appearance of the large electric field that is generated resonantly also differs in mode numbers. All of these modes should be included to realize the actual wave behavior.

## 3. Calculation results

The position of the power deposition is thought to be important for attainment of the good heating results. The relation of the position of the ion cyclotron resonance layers and the power absorption was investigated. Figure 2 shows the absorbed power as a function of the magnetic field strength. The central electron density and temperature are $1 \times 10^{19}$ m$^{-3}$ and 2 keV, respectively. Helium plasma with 10 % of hydrogen ion is assumed. The absorption by hydrogen ion is very strong as shown in broken-dotted line. If the ion cyclotron resonance layer of hydrogen exists in the plasma, most of the radio-frequency power is absorbed by the hydrogen ions. The wave frequency is 38.47 MHz. When the magnetic field is 2.75 T, the ion cyclotron resonance layers are located around the saddle-point of the magnetic configuration. In this case, the heating efficiency by the ICRF heating was best in the LHD experiments [1-4]. The resonance layer lies on the magnetic axis in $\varphi = 0°$ when the magnetic field is 2.5 T. Different from the experiments, the strong power absorption occurs when the resonance layers are located between the saddle-point and the magnetic axis. This tendency is the same as the case that the calculation is carried out by using one toroidal mode.

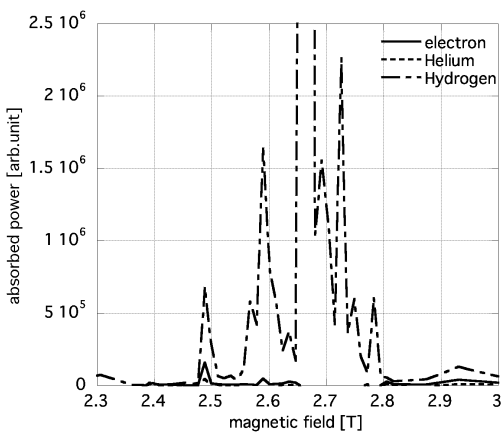


Fig. 2 Power absorption dependence on magnetic field. Solid, broken, and broken-dotted lines are the power absorption by electron, helium, and hydrogen, respectively.

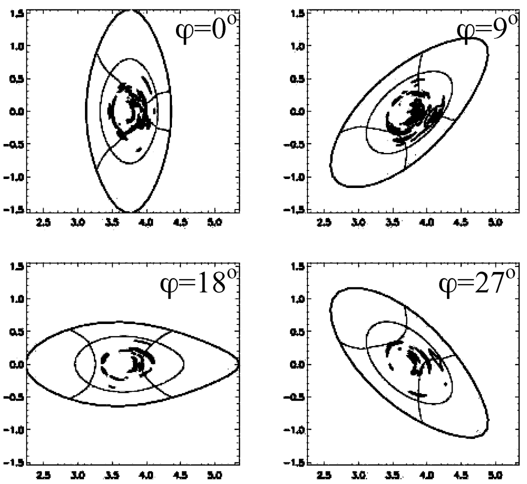


Fig. 3 Absorbed power in poloidal cross-section. Magnetic field is 2.75 T. $\varphi$ is toroidal angle. Antenna is located at $\varphi$ = 0°. Ion cyclotron resonance layer, vacuum vessel and plasma surface are also plotted.

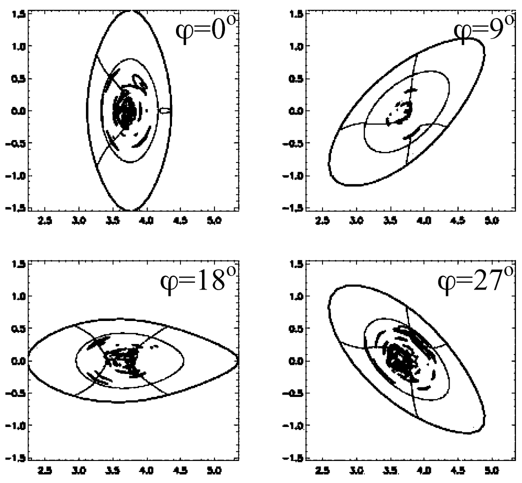


Fig. 5 Absorbed power in poloidal cross-section. Magnetic field is 2.61 T.

Figures 3, 4 and 5 show the power deposition profiles on the poloidal plasma cross-section in the case of 2.75, 2.5 and 2.61 T, respectively. The ion cyclotron resonance layers are also plotted. The antenna is installed at the toroidal angle of $\varphi$ = 0°. In figure3, the gap between the resonance layers is relatively small at $\varphi$ = 0° and effective heating is expected in this saddle-point heating configuration. However, at other toroidal angles the resonance layers are located relatively outer region of the plasma and the gap is wider. In 2.5 T, the resonance layers are located near the saddle-point only at $\varphi$ = 18° as shown in figure 4. One resonance layer lies on the magnetic axis at $\varphi$ = 0, 9 and 27°. The power deposits in the relatively narrow region in the radial power deposition profile. In the region between 2.5 T and 2.75 T, the resonance layers are located near the saddle-point in the wider toroidal angle as shown in figure 5. The wave power is absorbed not only at the vicinity of the antenna but also at $\varphi$ = 9 and 27°. Importance of the saddle-point heating is predicted by the broadening of the resonant region caused by the gentle gradient of the magnetic field [2]. Though we have cared the configuration of the ion cyclotron resonance layers at the poloidal cross-section where the antenna is installed ($\varphi$ = 0°) mainly, we should pay more attention to the other toroidal angles.

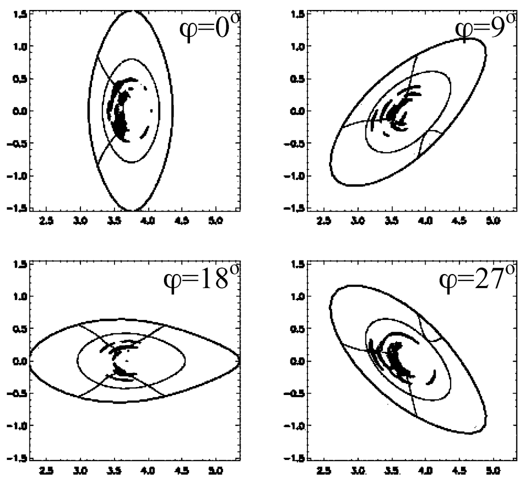


Fig. 4 Absorbed power in poloidal cross-section. Magnetic field is 2.5 T.

## 4. Summary

The ICRF heating in the helical device is investigated using the three-dimensional full-wave code, TASK/WM. Dependence of the power absorption on the position of the ion cyclotron resonance layer is studied in detail and strong ion absorption is obtained when the resonance layer is situated between the saddle-point and the magnetic axis. The position of the ion cyclotron resonance layer differs in the different toroidal angles even in the same magnetic field and the wave frequency. The position of the resonance layer not only at the toroidal angle which antenna is installed but also at other toroidal angles is important for the effective ICRF heating for the helical plasmas.

## References

[1] T. Seki *et al.*, *14th Top. Conf. RF Power in Plasmas,* 67 (2001).
[2] K. Saito *et al.*, Nucl. Fusion **41**, 1021 (2001).
[3] T. Mutoh *et al.*, *IAEA Conference*, Lyon, IAEA-CN-94/EX/P2-19 (2002).
[4] R. Kumazawa *et al.*, Plasma Phys. Control. Fusion **45**, 1037 (2003).
[5] T. Seki *et al.*, J. Plasma Fusion Res. SERIES **5**, 478 (2002).
[6] V.L. Vdovin *et al.*, NIFS-469 (1996).
[7] A. Fukuyama *et al.*, *IAEA Conference*, Sorrento, IAEA-CN-77/THP2/26 (2000).
[8] S.P. Hirshman *et al.*, Comp.Phys. Comm. **39**, 161 (1986).