

High harmonics fast wave experiments in the Large Helical Device

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1. Introduction

HHFW has higher harmonics number of ion cyclotron range of frequencies (ICRF), and the wave accessibility to plasma core for various electron densities ($> 10^{19} \text{ m}^{-3}$) is good [1]. If ion cyclotron damping is weak and excited wave number is suitable to heat electrons for electron Landau damping (ELD) and transit-time-magnetic-pumping (TTMP), single-pass-damping to electrons is extended as electron beta is increased. Electron heating experiment using HHFW was challenged in the Large Helical Device (LHD) at 2004 [2]. While electron beta was small and it was damped by multi-passes, clearly electron heating was achieved over a certain electron density at plasma core ($n_e = 2 \times 10^{19} \text{ m}^{-3}$). According to simple 1-dimensional calculation for electron heating, heating efficiencies are almost same around $n_e = 10^{19} \text{ m}^{-3}$ in the LHD. For studying multi-pass-damping effect with low ICRF resonances in

the LHD, HHFW experiment were tried for various electron densities in 2006.

2. Electron heating experiments for low electron densities

Magnetic field is 1.5 T at $R = 3.6 \text{ m}$, and some ICRF resonances (Helium: 3rd, 4th and 5th, Hydrogen: 2nd) are shown in Fig. 1. Since ICRF harmonics numbers of Helium are not small, ion cyclotron damping is difficult without 2nd Hydrogen harmonic heating. Fast wave excitation antennas (frequency: 38.47 MHz) which consisted of a single loop strap were installed on high filed side near $R = 4.2$

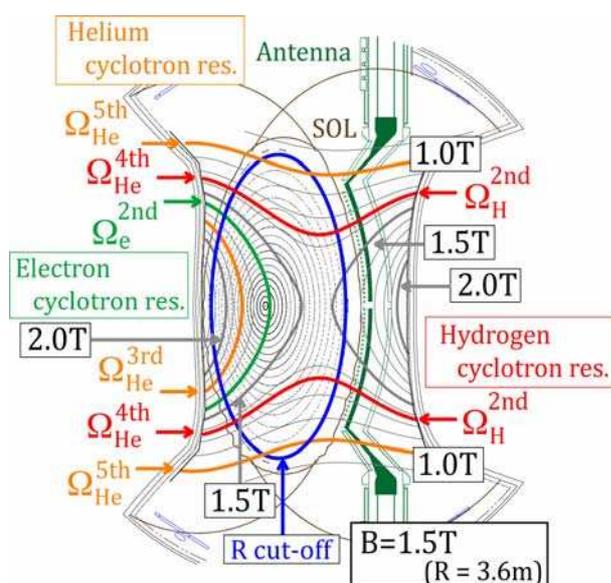


Fig. 1 ICRF harmonics resonances (Helium: 3rd, 4th and 5th. Hydrogen: 2nd) for $B_T = 1.5 \text{ T}$, and electron cyclotron resonance is close to plasma core.

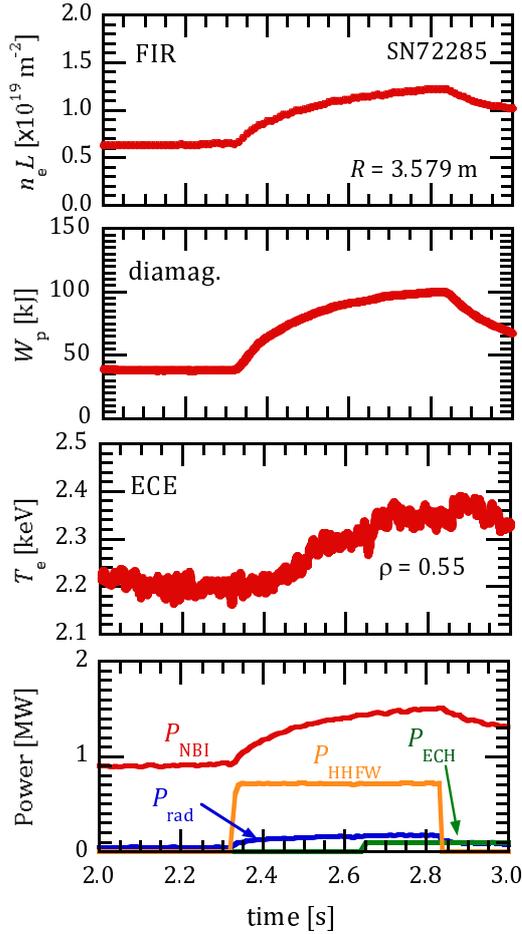


Fig. 2 Time evolutions for plasma parameters, electron density $n_e L$, stored energy W_p , electron temperature T_e (ECE), Radiation loss power P_{rad} (Bolometer), Net heating power P_{HHFW} (HHFW), P_{ECH} (ECH) and deposition power P_{NBI} (NBI) in plasma discharge

density increment. At that time, electron temperature at $\rho = 0.55$ has a response time to increase T_e and the response time is approximately 20 ms. It is smaller than energy confinement time (40 ms), and electron pressure at $\rho = 0.55$ has a no response time. According to ion tail measurement by SiFNA, ion tail expansion is observed during HHFW injection, it is produced by 2nd Hydrogen harmonics heating. Compared with an ion-electron energy slowing down time τ_{ie} by ICRF accelerated ion particles, τ_{ie} is approximately 90 ms, and the response time is much smaller than the slowing down time.

Figure 3 shows the detail of the time evolution (T_e , W_p , electron pressure $n_e T_e$, P_{HHFW} and P_{NBI}) at HHFW injections. Electron pressure is estimated to multiply electron density by FIR and electron temperature by ECE at $\rho = 0.74$. After HHFW is injected at $t = 2.32$ sec, T_e , $n_e T_e$ and W_p is increased at almost same time. For electron temperature response times are different from $\rho = 0.55$ and $\rho = 0.74$, though there are no response times for electron

m. Magnetic configuration is different from tokamak one, and magnetic field is small at the plasma core, and it is high in both sides to short axis of ellipse shape. Owing to these magnetic configurations, core electron heating is strong for 10^{19} m^{-3} in the LHD, and it is easy to heat core electrons.

Figure 2 shows time evolutions of plasma parameters; line integrated electron density $n_e L$ by far infrared reflectometer (FIR), stored energy W_p by diamagnetic coils, electron temperature T_e by electron cyclotron emission (ECE), heating power and radiation losses P_{rad} . P_{HHFW} is net heating power for HHFW, and P_{ECH} is absorption power for ECH and P_{NBI} is a deposition power for NBI. Though majority ion is Helium, there is a few amount of Hydrogen, and ion tail heating by 2nd Hydrogen harmonics ICRF heating [3] is suggested. After HHFW is injected at $t = 2.32$ sec, P_{HHFW} is almost constant (720 kW), and $n_e L$, W_p and P_{rad} are increased, and P_{NBI} is changed by

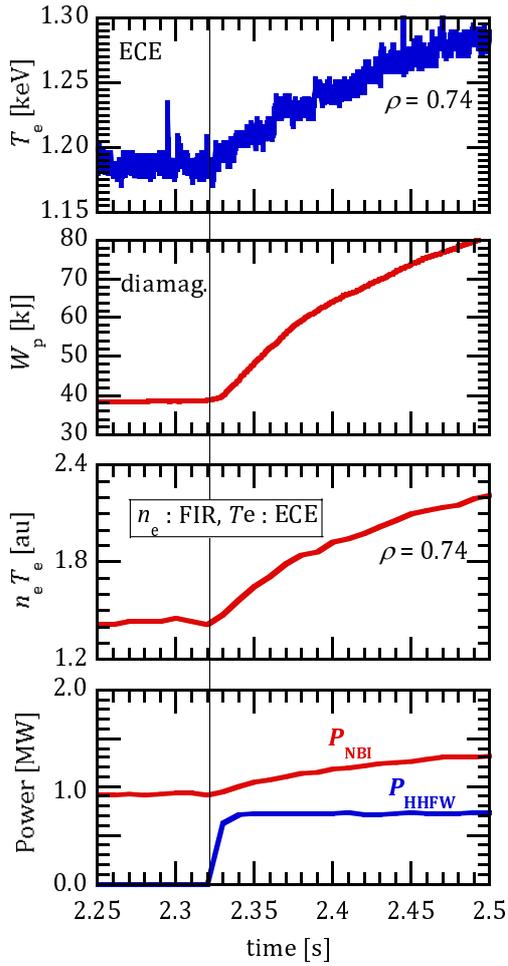


Fig. 3 Time evolution for electron heating at HHFW injection ($t = 2.32$ sec). Electron pressure is estimated to multiply n_e (FIR) and T_e (ECE).

pressure $n_e T_e$ in each positions. Electron pressures are increased with no response times and electron density is increased at the same time, and heated electron energy by density is small and the difference of T_e is unclear for ECE measurements. In this experiment direct electron heating may be achieved in $\rho > 0.55$.

Considering with heating effect of P_{NBI} increment, heating efficiency is estimated using following equations $P_{\text{HHFW}}^{\text{abs}} = dW_p/dt|_{(2)} - dW_p/dt|_{(1)}$. Since the difference time between (1) and (2) is less than 15 ms, plasma parameters are roughly not changed. However $\Delta P_{\text{NBI}} (= P_{\text{NBI}}|_{(2)} - P_{\text{NBI}}|_{(1)})$ is not negligible, and these effects are deduced and heating efficiency $\eta (= P_{\text{HHFW}}^{\text{abs}} / P_{\text{HHFW}})$ is calculated to Fig. 4. These circles $\eta^{\text{EXP.}}$ are experimental heating efficiency and these squares $\eta^{\text{single-pass calc.}}$ are single-pass-damping efficiency based on simple 1-dimensional calculation. As

electron density is increased, single-pass-damping is increased and heating efficiency is increased. However single-pass-damping is less than a few %, and heating efficiency is high, and they are suggested that helical magnetic configurations are suitable for HHFW heating rather than tokamaks.

Figure 5 shows simple 1-dimensional calculation results, and these initial parameters are same to actual experimental parameters in the LHD: Wave frequency is 38.47MHz, excited wave number is 8 m^{-1} and Helium discharge. (a) $n_e = 0.3 \times 10^{19}$ (dotted-line), (b) 0.6×10^{19} (line). T_e (parabolic) = 2 keV and $B_T = 1.5\text{T}$. Figure 5-I shows the calculation results for propagation regions of excited wave. If electron density is over $0.6 \times 10^{19} \text{ m}^{-3}$ (b), wave accessibility is good, and effective electron heating region is moved from $R = 3.84 \text{ m}$ (a: $\rho = 0.6$, $n_e = 0.3 \times 10^{19} \text{ m}^{-3}$) to $R = 3.72 \text{ m}$ (b: $\rho = 0.3$, $n_e = 0.6 \times 10^{19} \text{ m}^{-3}$) in Fig. 5-II. In this calculation for $n_e = 0.3 \times 10^{19} \text{ m}^{-3}$, electron heating is effectively carried out near $\rho = 0.6$, and it is close to the direct electron heating region with a no response time for ECE measurement.

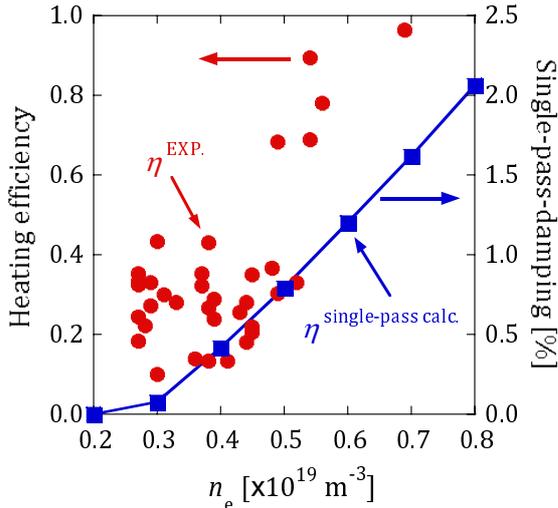


Fig.4 Heating efficiencies for various core electron densities. They are estimated by the difference of stored energy at the time when HHFW turns on and turns off.

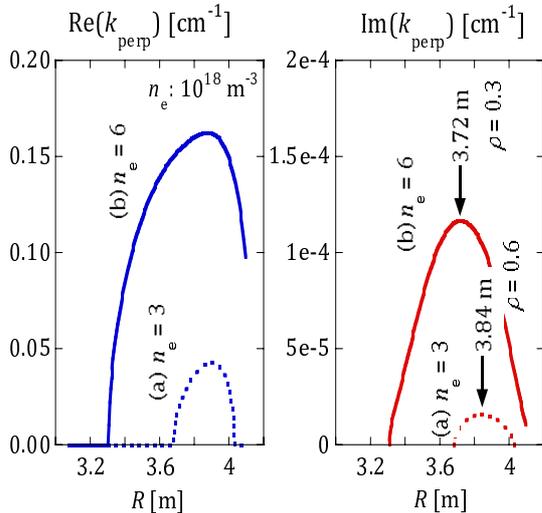


Fig.5 Simple 1-dimensional calculation for HHFW. ELD and TTMP are included to heat electrons. (I): real part of perpendicular wave number k_{perp} , and (II): imaginary part of k_{perp} , $T_e = 2$ keV (parabolic profile), freq. = 38.47MHz and initial wave number is 8 m^{-1} . Electron density is flat profile ($1-\rho^5$), and (a) $n_e = 0.3 \times 10^{19} \text{ m}^{-3}$, and (b): $n_e = 0.6 \times 10^{19} \text{ m}^{-3}$.

As electron density is increased to $n_e = 0.6 \times 10^{19} \text{ m}^{-3}$, single-pass-damping is increasingly strong, and direct electron heating region is extended, and direct core electron heating is achieved. This characteristic of HHFW electron heating is kept to high density plasmas (10^{21} m^{-3}).

3. Summary

With low order ICRF resonances, electron heating experiments using HHFW are tried in the LHD, and 2nd ion cyclotron heating and HHFW heating are observed at the same time. Even if single-pass-damping is less than a few %, direct electron heating is achieved, and effective heating region is outward from plasma core, and the region is close to simple 1-dimensional calculation. Though direct electron heating region is not plasma core for low electron density ($0.3 \times 10^{19} \text{ m}^{-3}$), heating efficiency is approximately 30%. Since HHFW can heat electrons for various electron densities (from 10^{18} to 10^{21} m^{-3}) with multi-pass-damping, it is suggested that HHFW is important key role to heat Super Dense Core plasmas in the LHD [4].

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References

- [1] M. Ono, Phys. Plasmas 2, 4075 (1995)
- [2] H. Kasahara, et al., Journal of Korean Physics 49, S192 (2006)
- [3] K. Saito, et al., Plasma Phys. Control. Fusion 44, 103 (2002)
- [4] N. Ohya, et al., Phys. Rev. Lett. 97, 055002 (2006)