Electron Heating Experiment Using the High Harmonic Fast Wave on LHD

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Electron heating experiments using the High Harmonic Fast Wave (HHFW) were performed on
the Large Helical Device (LHD). An electron temperature increase from 2.5 keV to 3.6 keV by
1.2 MW of HHFW was observed when both ECH and NBI were used to create a target plasma
with high stored energy and electron temperature. When ECH works effectively, the electron
density is pumped out, but the rate of decrease of the electron density is reduced when HHFW
heating is applied. This result indicates that HHFW is absorbed effectively when the central
electron temperature and electron beta are high enough, and suggests that parallel heating of
electrons by HHFW reduces electron density pump out caused by perpendicular electron heating
by ECH. According to a 1-D calculation, raising the density is more effective for improving single-
pass damping than raising the temperature. According to a 2-D full-wave calculation, electron
damping occurs in an off-axis region at low density, but wave fields become more concentrated
in the core and absorption becomes more centrally localized at high density.

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I. INTRODUCTION

The high harmonic fast wave (HHFW) is an attractive
wave that can be used for heating and current drive in
high $\beta$ plasmas. Since the frequency of HHFW is much
higher than the ion cyclotron frequency, electron Landau
damping (ELD) and transit time magnetic pumping
(TTMP) dominate over ion cyclotron harmonic damp-
ing, and absorption becomes stronger as $\beta$ is increased
[1]. In order to demonstrate electron heating clearly,
HHFW experiments were carried out on the Large Helical Device (LHD) [2]. As a first step, existing ICRF
transmitters at a frequency of 38.45 MHz were used at
a reduced magnetic field of 1.5 T. Under this condition,
the ion cyclotron harmonic numbers are greater than 3
for helium majority ions and greater than 2 for hydro-
gen minority ions. When the second harmonic hydrogen
resonance is present, HHFW could be damped by ions.
In Sec. II, experimental setup and the target plasma
for the heating experiment are described. In Sec. III,
effects of HHFW injection on electron and ion temper-
atures, electron temperature and density profiles, and
stored energy are presented. In Sec. IV, results of a 1-
dimensional (1 D) single-pass absorption calculation and
a 2-dimensional (2 D) full-wave code (TASK/WM [3])
are presented. Finally, experimental and calculated re-
sults are compared in Sec. V.

II. EXPERIMENTAL SETUP AND TARGET
PLASMA

Figure 1 shows the ICRF antenna [4-6] used to ex-
cite the HHFW for this experiment. This is a single-loop
antenna with the Faraday shield approximately aligned
to the boundary magnetic field lines. Both sides of the
antenna are protected by carbon tiles. The characteris-
tic width of the wavenumber spectrum excited by this
antenna is $\Delta k = 5$ m$^{-1}$.

Figure 2 shows a typical He discharge at $B_{\tau_{h}} = 1.5$ T
with only a very short HHFW pulse. This discharge will
be used as a reference to evaluate the effects of HHFW
injection. During electron cyclotron heating (ECH), ef-
effective electron heating occurs at the plasma center ($R =$
The central electron temperature $T_{e0}$ increases from an initial level of 2.2 keV to a level of 2.8 keV to 2.9 keV. The temperature increase was observed in the core region from $R = 3.3$ m to $R = 4.0$ m. Soft X-ray radiation also increased in the core. However, $T_{e0}$ subsequently decreases to 2.6 keV by the end of the ECH pulse. The line integrated and central electron densities both decreased during ECH (density pump-out) [7]. The central ion temperature also decreased slightly, and the stored energy decreased by about 20 kJ during ECH.

### III. HHFW HEATING EXPERIMENT

In this Section, experimental results from the HHFW heating experiment are presented. In order to estimate the absorbed HHFW power and its profile, changes in the stored energy, the central ion temperature, and the electron temperature and density profiles are examined.

#### 1. Electron and ion heating

Figure 3 shows comparisons of the central electron and ion temperatures for different HHFW powers. The shot shown by the solid line had only a short pulse low power HHFW injection (same as Figure 2). In discharges with longer, higher power HHFW injection, the electron temperature increased to 3.6 keV, while there was little change in the ion temperature. These results are consistent with HHFW absorption by ELD and TTMP which become effective at high $T_e$ and high $\beta_e$. Under the present condition, single pass absorption for HHFW is still weak. After ECH turns off, high $T_e$ cannot be maintained, and HHFW damping deteriorates rapidly.

#### 2. Stored energy changes

In order to estimate the HHFW absorption efficiency, the time evolution of the plasma stored energy $W_p$ is analyzed. Two levels of initial stored energy, 240 kJ ($n_e l = 2.2 \times 10^{19} \text{ m}^{-2}, T_{e0} = 2.6 \text{ keV}$) and 255 ~ 260 kJ ($n_e l = 3.0 \times 10^{19} \text{ m}^{-2}, T_{e0} = 2.6 \text{ keV}$) are compared in Fig. 4.
Fig. 4. Time evolutions of (a) stored energy and (b) its time derivative. $P_{HFW} = 0.4$ MW (solid line); $P_{HFW} = 0.6$ MW (dot line); $P_{HFW} = 1.2$ MW (dashed line); $P_{HFW} = 0.3$ MW (long dashed line); $P_{HFW} = 1$ MW (dash-dot line).

Fig. 5. Absorbed HHFW power $P_{abs}$ (solid circles) and absorption efficiency $P_{abs}/P_{HFW}$ (solid squares) as functions of $P_{HFW}$.

The HHFW injection power varied in the range 0.3 to 1.2 MW. ECH causes $W_p$ to decrease because of the density pump-out effect. The application of HHFW power clearly changes $dW_p/dt$ and $W_p$ saturates after an incremental confinement time of about 0.05 s, which is shorter than the electron confinement time. The absorbed HHFW power is evaluated as the change in $dW_p/dt$ at HHFW turn-on, $P_{abs} = \Delta(dW_p/dt)$. $P_{abs}$ increases linearly with $P_{HFW}$ and the absorption efficiency $P_{abs}/P_{HFW}$ is constant around 32%, as shown in Figure 5. Time evolutions of the line integrated electron densities $n_e l$ along the central chord ($R = 3.6$ m) and an off-axis chord ($R = 3.8$ m) are plotted in Figure 6. The electron density decreases during ECH (density pump-out [8]) due to perpendicular heating of electrons. The rate of decrease of the electron density is reduced when HHFW power is applied, suggesting that parallel heating alleviates the density pump-out effect. The density decrease prevents $W_p$ from increasing because of the positive dependence of $W_p$ on $n_e$. The central electron pressure $P_{e0}$ decreases by about 40% when only ECW is injected. However, with the application of HHFW power, a nearly constant pressure is maintained.

IV. CALCULATION OF HHFW ABSORPTION

In order to estimate absorption of HHFW power, a simple 1-D single-pass absorption calculation and the TASK/WM 2-D full-wave code were used to estimate the absorption of HHFW power.

1. Single-pass absorption calculation

In the 1-D calculation discussed here, HHFW is assumed to propagate along the major radius at $z = 0$. The region of propagation (shown as the region where $\text{Re}(k_\perp) > 0$) and the inverse damping length $\text{Im}(k_\perp)$ are shown in Figure 7. Profiles of electron temperature, density, and magnetic field were kept fixed while $T_e$ and $n_e$ were varied. Increasing $T_{e0}$ from 2.5 keV to 3.5 keV increases $\text{Im}(k_\perp)$ by 25%, and the single-pass absorption increases from 3.3% to 4.0%. On the other hand, increasing $n_{e0}$ from $1.8 \times 10^{19}$ m$^{-3}$ to $3.6 \times 10^{19}$ m$^{-3}$ increases $\text{Im}(k_\perp)$ by a factor of 4.8, and the single-pass absorption increases to 11.3%. It is also apparent that the region of propagation has increased with density (D to E to G). It is concluded that raising the density contributes to increasing the single-pass damping more effectively than raising the temperature.
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Fig. 7. (A) Electron temperature profile, (B) electron density profile, and (C) magnetic field profile used for single-pass absorption calculation. (a) Re($k_\perp$) and (b) Im($k_\perp$) derived from the hot plasmas dispersion relation for $k = 5 \text{ m}^{-1}$ (at the antenna position), and $B_0 = 1.5 \text{ T}$ (at $R = 3.6 \text{ m}$): (D) $T_{e0} = 2.5 \text{ keV}$, $n_{e0} = 1.3 \times 10^{19} \text{ m}^{-3}$; (E) $T_{e0} = 2.5 \text{ keV}$, $n_{e0} = 1.8 \times 10^{19} \text{ m}^{-3}$; (F) $T_{e0} = 3.5 \text{ keV}$, $n_{e0} = 1.8 \times 10^{19} \text{ m}^{-3}$; (G) $T_{e0} = 2.5 \text{ keV}$, $n_{e0} = 3.0 \times 10^{19} \text{ m}^{-3}$.

Fig. 8. Power absorption profiles calculated by TASK/WM. for $B_0 = 1.5 \text{ T}$ ($R = 3.6 \text{ m}$), $T_{e0} = 2.5 \text{ keV}$, and (A) $n_{e0} = 1.3 \times 10^{19} \text{ m}^{-3}$, (B) $n_{e0} = 1.8 \times 10^{19} \text{ m}^{-3}$.

2. Full-wave analysis

TASK/WM is a full-wave code that solves the differential wave equation with a conducting boundary condition. It calculates the total absorption profile by each species (the sum of integrated absorption power is equal to the injected power). It cannot differentiate absorption per pass, but is useful to determine the total (multiple-pass) absorption profiles and the fraction of power absorbed by each species. According to TASK/WM, electron damping occurs in the off-axis region of the plasma at low $n_{e0}$, but wave fields become more concentrated in the core and absorption becomes more centrally localized at high $n_{e0}$, as shown in Figure 8. The density dependences of the single-pass absorption from the 1-D calculation and the absorbed power per unit antenna current from TASK/WM are shown in Figure 9. The single-pass absorption increases nearly linearly with density above $n_{e0} \approx 1.3 \times 10^{19} \text{ m}^{-3}$. On the other hand, the absorbed power per unit antenna current (corresponding to the radiation resistance, which is an indication of antenna-plasma coupling) decreases exponentially as the density is reduced below $5 \times 10^{19} \text{ m}^{-3}$. This is caused by an increased evanescent region as $n_{e0}$ is lowered. Both of these effects indicate that higher densities are favorable. In the present experiment $n_{e0}$ is about $2 \times 10^{19} \text{ m}^{-3}$, so the single-pass absorption is expected to be less than 5%. The absorption efficiency of $\sim 32\%$ obtained experimentally is much higher than the calculated single-pass absorption, suggesting the importance of multi-pass absorption.

V. CONCLUSIONS

In order to develop a method to heat electrons in high $\beta$ plasmas with high dielectric constant, HHFW experiments were carried out on LHD. In this experiment the second harmonic resonance of minority hydrogen ions was present, and therefore there is a possibility of second harmonic ion cyclotron damping. However, electrons
were clearly heated while fast ion formation was not observed. HHFW heating was clearly demonstrated in a helical device for the first time. However, the absorption efficiency was only about 30%. In addition, density pump-out caused by ECH was reduced by HHFW heating. In the present experiment, the electron density was low, and the single-pass absorption was weak, calculated to be less than 5%. The increment of electron temperature was clearly better at higher densities. The calculated single-pass absorption increases nearly linearly with density above $n_e \sim 1.3 \times 10^{19} \text{ m}^{-3}$. On the other hand, the calculated radiation resistance decreases rapidly below $5 \times 10^{19} \text{ m}^{-3}$. In addition, absorption is predicted to be concentrated near the plasma center at high densities. According to these calculations, the electron density should be raised to about $5 \times 10^{19} \text{ m}^{-3}$ to achieve more effective electron heating.

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