Ion Bernstein Wave Heating Experiments on the HT-7 Superconducting Tokamak

Y. Zhao, J. LI and HT-7 Team

Institute of Plasma Physics, Chinese Academy of Sciences,
P.O.Box 1126, Hefei, 230031,P.R.China

Zhao_yp@mail.ipp.ac.cn

Abstract. Ion Bernstein Wave (IBW) heating has been investigated in HT-7 superconducting tokamak. The electron heating mode was concentrated on a deuterium plasma with an injection power up to 320kw. Direct electron heating via electron Landau damping from the IBW was observed. The bulk electron temperature showed a significant rise with a heating factor, $\Delta T_e \times n_e/P_{RF,}$ up to 7.4 ($eV \times 10^{13} cm^{-3}/kW$) and maximum increment of electron temperature was above 400 eV. IBW heating was combined with pellet injection, which also showed its unique merit.

1. Introduction

Ion Bernstein Wave (IBW) heating is an ion-cyclotron-resonance-frequency heating concept which uses the directly launched IBW to carry RF power deep into the dense plasma core. Strong ion heating is realized when the wave passes the resonant layers, where strong ion cyclotron damping occurs. Good ion heating results by IBW were observed on JIPP-II-U [1], PLT [2], PBX [3] and Alcator-C [4]. Some theoretical work and simulation codes were developed during the past few decades. Most of these efforts were concentrated on effective ion heating; fewer were concerned with electron heating and its mechanism.

IBW heating was also investigated in HT-7 superconducting tokamak deuterium plasma with an injection RF power up to 320kW. The bulk electron temperature shows a significant rise with a heating factor, $\Delta T_e \times n_e/P_{RF,}$ of 7.4 ($eV \times 10^{13} cm^{-3}/kW$). The maximum increment of electron temperature was above 400 eV. The fast increase of electron temperature and the low increment of ion temperature gave evidence that the electron heating was caused by electron Landau damping. The ion temperature rise was due to collision between ions and electrons.

2. Experimental set-up

HT-7 is a medium size superconducting tokamak with a limiter configuration. The major radius is 122 cm and the minor radius is 27.5 cm. The movable vertical limiter and horizontal pump limiter are made of molybdenum. The plasma current is about 120-200kA, and the toroidal magnetic field is about 1.5-2.0T. The plasma density is in the range of (0.5-5)×10^{13}cm^{-3}. The electron and ion temperatures are about 700eV and 400eV respectively. One of the main purposes of HT-7 experiments is to investigate steady-state operation by full lower hybrid wave current drive (LHCD). Higher electron temperature can benefit the current drive efficiency. In HT-7 the electron-heating mode for IBW heating experiments is concentrated on obtaining higher electron temperature.

The ICRF heating system for HT-7 has a 350kW continuous wave (CW) output power capability, and its frequency range is from 15 to 30MHz. The generator can be worked in short pulse, multi-pulse and steady state modes, permitting great experimental flexibility. The system includes RF generator, transmission lines, two stub tuners and an antenna. The IBW antenna is sited at equatorial plane on the low magnetic field side of the tokamak. Both central conductor and Faraday shielding are made of stainless steel. The radii of the central conductor and the Faraday shielding are 32cm and 28.5cm respectively. The maximum RF power of the generator is 350kw. Two step-tuners are used for the matching system. Deuterium working gas is adopted with a hydrogen minority. The toroidal magnetic field is chosen to make the Ω_H layer located in the central region of the plasma or off-axis. More than 30 diagnostic are operated for the measurement of plasma parameters. The fast ECE, soft x-ray diode array and fast moving Langmuir probe in particular are utilized for IBW heating experiments.

3. IBW Heating Experiments

HT-7 is running with a molybdenum limiter configuration for the IBW experiments. The plasma current is about 120-170kA and the toroidal magnetic field is about 1.5-2.0T. The plasma density is in the range of (1.5-3)×10^{13}cm^{-3}. The RF frequency was 24-30 MHz and the toroidal field was chosen to make the Ω_H layer located in the central region of the plasma. The electron heating of the IBW experiments was carried out in a deuterium plasma.

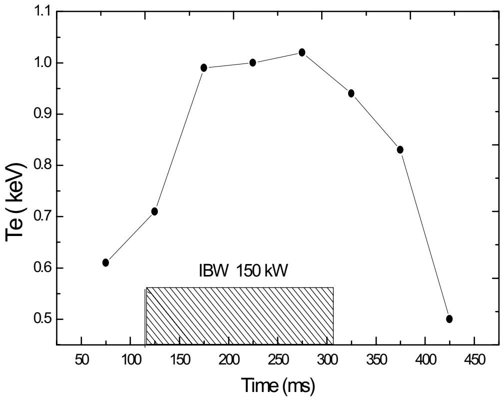

Fig.1. Electron temperature against time during IBW heating.

The electron heating results are shown in Fig.1. Around 150 kW RF power was injected into the tokamak. From Fig.1, one can see that when RF power was switched on, the electron temperature increased immediately, and after RF power was turned off, the electron temperature decreased. The maximum increase of the electron temperature was about 400eV. The toroidal magnetic field was scanned during the experiments. No strong correlation between heating efficiency and toroidal field was found within the Ω_H change of 10cm. The highest electron heating was observed at a density of $2.5\text{x}10^{19}\text{m}^{-3}$.

The edge plasma parameters are important for the IBW coupling physics. The ponderomotive force produced by the IBW may induce some negative effects for IBW heating. DIII-D results [5] suggest that the large ponderomotive potential causes the density in front of the antenna to drop significantly, which could be one of the reasons for poor coupling and little core heating. For these reasons, the edge plasma parameter was measured carefully with a fast moving Langmuir probe during IBW heating. It could give 1 mm spatial resolution. The probe quickly moved into plasma, within 50ms, and penetrated about 15mm during the flat-top of IBW heating. It remained at this position for about 100ms and was pulled back after the IBW was switched off. The different edge profiles could be obtained by this measurement. Figure 2 gives the edge plasma electron temperature and density (10mm inside the plasma) during the IBW heating. The results show that sharp gradients of electron temperature and density profiles inside the limiter were formed by IBW heating, and no significant density drop was observed.

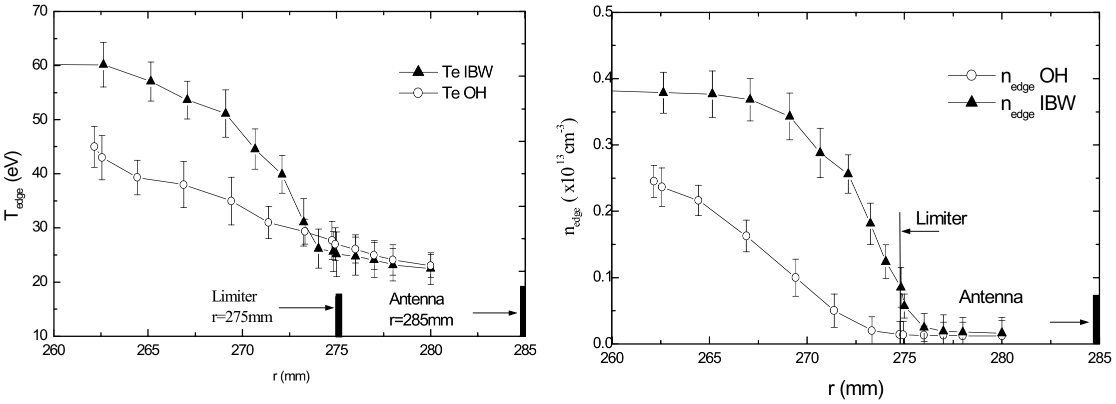

Fig.2. Edge electron temperature and density profiles for shot 22598.
P_{IBW}=110kW, f=30MHz, B_T=1.9T, Ip=145kA.

Particle confinement improvement was also observed during IBW heating, which is indicated by the drop of H_α, the increase of store energy and the suppression of edge fluctuation. A typical discharge is shown in Fig.3. As IBW is switched on, the particle confinement improvement phenomenon was seen immediately, but sometimes this phenomenon disappears before the IBW was switched off. This time duration of the improved particle confinement depends on IBW power. The higher the IBW power, the shorter the duration. This situation was thought to be due to the bad plasma quality caused by the impurity production in front of the antenna. RF wall conditioning [6] (RF wall cleaning and boronization) reduced the impurity production in front of the antenna greatly and very good confinement was obtained. A structure like an internal transport barrier (ITB) and a peaked density profile were also observed during IBW heating, as shown in Fig.4.

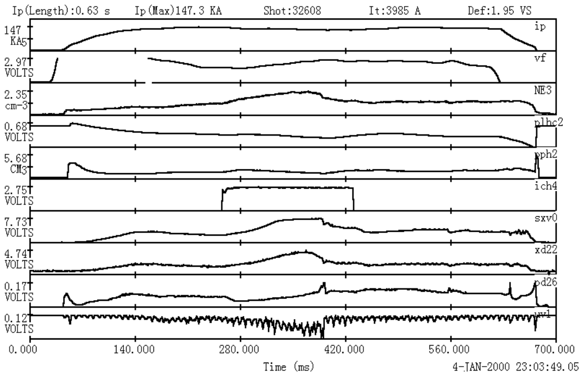

Fig.3. Particle confinement was improved by the IBW.
P_{IBW}=120kW, f=30MHz,B_T=1.9T.

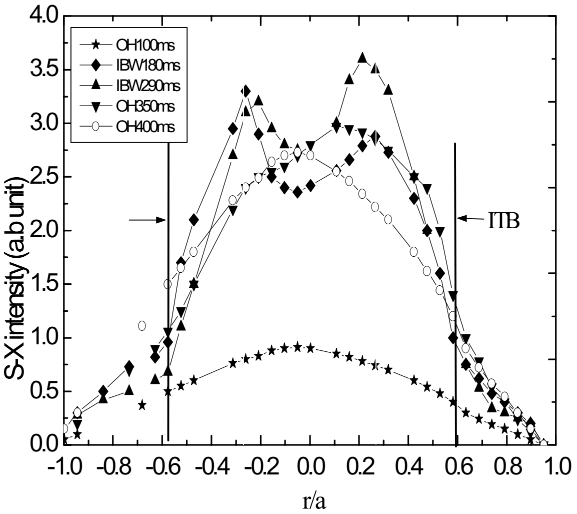

Fig.4. Soft x-ray Abel inversion for Fig.3.
An ITB-like structure was clearly shown at r/a = 0.6.
The Ω_H layer was observed at r/a =0.27.

IBW heating was also combined with pellet injection [7]. Fig.5 shows a typical discharge combining IBW heating and pellet injection. In comparison with the IBW heating phase, the confinement during the period of the H_α drop was improved by a factor of 1.6. Abel inversion of the soft x-ray array signals gave clear profiles for the different periods, as shown in Fig.6. During the improved confinement phase, the profiles became broader and a sharp gradient was formed around r =16cm (r/a=0.6). It seems that the sharp gradient at the region of normalized radius 0.6 acts as a transport barrier and plays a key role during the improved confinement phase.

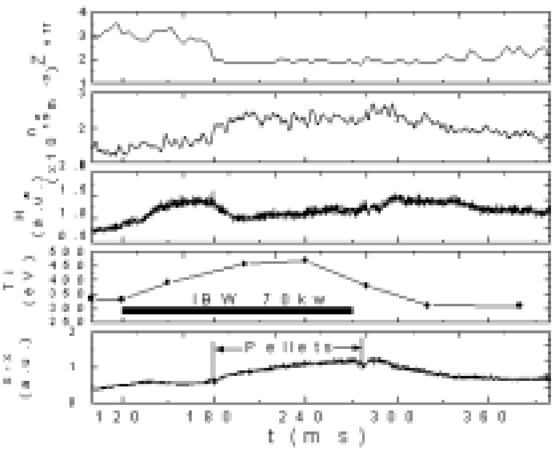

Fig.5. A typical shot with off-axis pellet and IBW heating. f = 27 MHz, B_T *= 1.45T,* Ω_H *= -13 cm,* I_P *=125kA.*

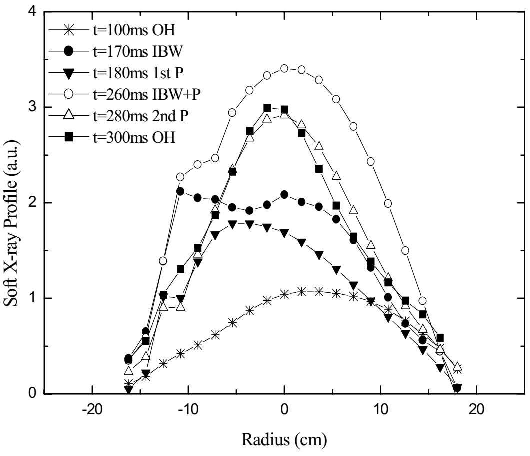

Fig.6. Abel inversion of soft x-ray array for Fig.5.

Conclusion

IBW heating was successfully carried out for the electron-heating mode after intensive RF boronization and helium cleaning. The maximum increment of electron temperature was about 400 eV. The heating factor reached 7.4 (eV×10^{13}cm^{-3}/kW). The maximum input RF power was 320kW. The fast increase of electron temperature and the low increment of ion temperature gave evidence that the electron heating was caused by electron Landau damping. The ion temperature rise was due to collisions between ions and electrons. The edge plasma parameters were measured by a fast moving Langmuir probe. No significant density drop was observed during IBW heating. The impurity production and ionization in front of the antenna were greatly reduced by the good wall condition. Further accurate measurement and code simulations are still needed for better understanding of the mechanism of electron heating and particle confinement improvement.

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