IBW heating experiments in HT-7 tokamak

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Abstract. The Experiments with Ion Berstein wave (IBW) heating has been carried out in HT-7 superconducting tokamak. Core electron heating and peaking profile of electron temperature can be observed in the beginning 40 ms after injection of IBW. The temporary heating efficiency of IBW increases with the toroidal magnetic field ($B_T$). The electron temperature drops gradually with the increasing electron density after 40 ms of IBW. The electron density increases by a factor up to 2.4 and the profile of electron density becomes wide. Improved particle confinement induced by IBW is one reason for the density increase. Impurity release during IBW heating is also a contribution for the density increase. Suppression of MHD by IBW is also observed. The fluctuation and transport in the SOL of HT-7 tokamak have been investigated using a Langmuir probe array. The poloidal shear flow induced by IBW maybe the reason for improved particle confinement.

1. Introduction

Ion Bernstein wave (IBW) is a hot plasma wave with a frequency close to an ion cyclotron harmonic frequency, which is coupled directly to the plasma thermal ions and electrons by the ion cyclotron damping or electron Landau damping (ELD) that occurs near the resonant layer [1]. Theory and experiments have showed the advantage of IBW heating in different tokamaks. Both ion and electron heating via linear and nonlinear processes were observed in IBW experiments on quite a few devices [2-10]. IBW heating was also investigated in HT-7 deuterium plasma [11-16]. Enhanced particle confinement and suppression of MHD by IBW are usual phenomena in HT-7.

The HT-7 device is a medium-sized superconducting tokamak with a major radius of $R = 1.22$ m and is of a limiter configuration with two full poloidal limiters and one inner toroidal belt limiter, all of which are water-cooled and made of special doped graphite coated by SiC film with a minor radius of 27 cm. In the HT-7, the ICRF heating system has a 1.5 MW continuous wave (CW) output power capability and the operation frequency range is from 15 MHz to 110 MHz (30 MHz for IBW). The ICRF system includes RF generator, transmission lines, two stub tuners and two antennas (ICRF antenna and IBW antenna). IBW antenna is an asymmetric quadruple T-antenna with a central feeding and shorted ends. It was installed in the horizontal mid-plane on the low field side and oriented in the toroidal direction. The radii of central conductor and Faraday shielding are 32 cm and 28.5 cm respectively. The antenna center conductor is coated by TiN, and incorporated with graphite-doped protectors and Faraday shielding to reduce impurities.
2. Experimental results of IBW heating

The waveform of a typical discharge with 1.94 toroidal field ($B_t$) and 27 MHz IBW heating is shown in figure 1. The power of IBW was about 320 kW at flat top. The electron temperature was measured with a sixteen-channel electron cyclotron emission (ECE) grating polychromator (GPC) system [17]. The abrupt drop of $D_\alpha$ after the injection of IBW denoted the improved particle confinement. The electron temperature at $r = 3$ cm increased in the initial 40 ms of IBW heating. At the same time, the electron temperature at $r = -12.7$ cm was almost unchanged. The heat exchange time between electron and deuterium ion was about 100 ms. The electron should be directly heated by IBW. It can be seen in figure 2a the core plasma electron was heated by IBW and the profile of electron temperature become more peaked compared to that at OH heating. But the electron temperature of whole plasma dropped very much when electron density reached the flat top. Here, a simple temporary heating efficiency of IBW is defined as following,

$$\eta_{IBW} = \Delta T_e \frac{n_e}{P_{IBW}}$$

![Figure 1. Waveform for an IBW discharge. From top to bottom: $I_p$, the plasma current, $V_{loop}$, loop voltage, $n_e$, the center line average electron density, OV, the intensity of OV lines, SX, the intensity of soft x-ray at center, XUV, the radiation power measured with XUV detector, $T_e$, the electron temperature at $r = 3$ cm and $r = -12.7$ cm, $P_{IBW}$, the power of IBW, $D_\alpha$, the radiation of $D_\alpha$, $W_{diss}$, the store energy measured by diamagnetism, $\tau_e$, the energy confinement time.](image)
Figure 2a. The profiles of the electron temperature of the same shot in figure 1. IBW was injected at 190 ms.

Figure 2b. The heating effect of IBW with different power at $B_T = 1.94$ T.

Figure 3. Waveforms for IBW shots with different $B_T$.

where $\Delta T_e$ is maximum value in IBW heating phase, $n_{e0}$ is the center line average density at the time of $\Delta T_e$, $P_{IBW}$ is the power of IBW at that time. The heating effect of different power of IBW with the same target plasma parameters ($n_{e0}$ (OH) = $1.4\times10^{19}$m$^{-3}$, $B_T = 1.94$ T) are show in figure 2b. The heating efficiency of IBW is consistent and not changed with the power of IBW. The heating effect of IBW with different $B_T$ was also investigated. Figure 3 shows the waveform of three discharges with IBW heating. All of parameters are the same except $B_T$. The power of IBW was about 300 kW at flat top in these shots. The profiles of $T_e$ at $B_T = 1.85$ T and 1.76 T are shown in figure 4a. It can be seen the core plasma was still heated in lower toroidal filed. It seems like the power deposition profile on electron of 27 MHz IBW at this target plasma was unchanged with toroidal magnetic filed. On the other hand, the temporary heating efficiency of IBW increased with $B_T$ (as shown in figure 4b). At the same time, both the growth rate and the maximum value of electron density during IBW heating were higher in lower $B_T$ plasma (as shown in figure 4). The impurity (OV) had the similar behavior as electron density.
The electron density in HT-7 was measured with a five-channel far-infrared (FIR) hydrogen cyanide (HCN) laser interferometer [18]. The exact density profile is quite difficult to be deduced from this diagnostics. The ratio of $n_{e0}/n_{e20\text{cm}}$ ($n_{e20\text{cm}}$ is the line average density at $r = 20$ cm) can denote the peaked degree of the electron density profile. Figure 5a shown the time evolution (the same discharge as in figure 1) of $n_{e0}/n_{e20\text{cm}}$, $n_{e0}$, and $T_e$. The electron temperature dropped gradually with the increasing electron density after 40 ms of IBW. The $n_{e0}$ increased from 1.4 to $3.4 \times 10^{19}$m$^{-3}$ while the center $T_e$ dropped to half as that in OH heating. The electron density profile became wider and wider in the initial 80 ms of IBW heating and kept the width in the later time, however, the radiation profiles (as shown in figure 5b) measured with a XUV bolometer array became more peaked with time. There are two possible reasons for the peaked XUV profiles. One maybe the impurity concentration in center plasma. The other maybe the edge electron temperature during IBW heating became too low and radiation from this part cannot be effectively detected by XUV array. The impurity spectra measured with a PI SP-300i spectrometer are also shown in figure 6. The light impurity line can be observed from the spectra. Boronization is main wall cleaning method in HT-7. The boron film in these discharges with IBW heating is neither fresh nor old. The distinct increase of carbon and boron lines from the peripheral plasma ($r = 20$ cm) indicated that quite a number of impurities entered to the plasma during IBW heating. Compared to the peripheral plasma, only OV and CVI charge-exchange line from the center plasma increased during IBW heating. The reason is only the highly stripped impurity ions can penetrate the center plasma due to the higher electron temperature in center plasma. So the contribution from the impurity is also a considerable mechanism for the density increase during IBW heating. The maximum heating efficiency of 27 MHz IBW was no more than 0.75 (as shown in figure 4b). The limited heating effect of IBW was counteract and greatly exceeded by the cooling
effect due to the increasing electron density and impurity radiation, which might be the main reason for the gradual decrease of the electron temperature during the later phase of IBW heating.

**Figure 5a.** Time evolution of \( n_{e0} / n_{e20cm} \), \( n_{e0} \), and \( T_e \).

**Figure 5b.** The profiles of radiation power measured with XUV array.

**Figure 6.** The spectra of IBW shot. The intensity had been normalized by electron density.
Improved particle confinement and suppression of MHD are ordinary phenomena in IBW heating plasma in HT-7. It can be seen in figure 7 the drop of $D_e$ and suppression of MHD simultaneously appeared during IBW heating. The fluctuation and transport in SOL had been investigated using a Langmuir probe in previous 30 MHz IBW heating experiments in HT-7 [13, 16, 19]. Both heat flux and particle flux in SOL decreased during IBW injection (as shown in figure 8a). $B_t$ was 1.92 T in the 30MHz IBW heating experiment with Langmuir probe, which made the $5/2\Omega_e$ layer located in the plasma edge of $r \approx 26$ cm on the low field side, where an IBW is expected to induce sheared flows. Such sheared flows were indeed observed with Langmuir probe. The results of Langmuir probe showed the averaged poloidal phase velocity of turbulence turned from the ion diamagnetic direction to the electron diamagnetic direction in the SOL after IBW switched on. An additional inward (negative) $E_r$ was generated in the plasma edge during IBW heating (as shown in figure 8b). The structure of clear $E_r$ wells and the obvious increase of $E_r$ shear can be seen in this figure. The shearing rate, $\omega_{E\times B}$, of a turbulent structure in IBW-heating phase exceeded the ambient turbulence decorrelation rate, $\Delta\omega_D$, for the drift-wave-like turbulence. This strong shear decorrelation effect produced a distinct weak turbulence regime in the boundary plasma and might account for the improved particle confinement.

![Figure 7](image1.png)

*Figure 7. The discharge with IBW modulation.*

![Figure 8a](image2.png)

*Figure 8a. Profiles of heat flux (up part) and particle flux (low part) in SOL.*

![Figure 8b](image3.png)

*Figure 8b. Profiles of the radial electric filed in SOL.*
3. Summary
The electron heating effect by 27 MHz IBW was investigated in the deuterium plasma on HT-7. The core plasma electron heating could be obviously observed in the initial 40 ms during IBW injection. It seems like the IBW power deposition profile on electron at this target plasma was unchanged with \( B_T \). But the temporary heating efficiency of IBW increased with \( B_T \). Except for the improved particle confinement, the contribution from the impurity is also a considerable source for the density increase during IBW heating. The limited heating effect of IBW was counteract and greatly exceeded by the cooling effect due to the increasing electron density and impurity radiation, which might be the main reason for the gradual decrease of the electron temperature during the later phase of IBW heating. With the measurement of Langmuir probe, an additional inward (negative) \( E_r \) was observed in the plasma edge during IBW injection. This strong \( E_r \) shear decorrelation effect produced a distinct weak turbulence regime in the boundary plasma and might account for the improved particle confinement.

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