LOWER HYBRID ION HEATING ON HL-1M TOKAMAK

X.T. Ding, Y. Liu, J.Q. Zhang, D.M. Xu, G.W. Zhong, J.Y. Cao,

X.M. Song and E.Y. Wang

Southwestern Institute of Physics, Chengdu 610041, P.R. China

The lower hybrid heating (LHH) experiments were performed on HL-1M tokamak with major radius R=102cm, minor radius a=26cm, toroidal magnetic field B_t =2.4T and plasma current I_p>90kA. The lower hybrid wave(f_{LH}=2.45GHz) was launched at the weak magnetic field side of the torus by a 2×12 waveguide grill ($\Delta \Phi = \pi /2$, $N_{//}$=2.6). The power of LHW is about 200-400kW with 100ms pulse width. More than 30 typical diagnostics have been installed around the tokamak. Ion temperature is measured by a 6-channel charge exchange analyzer. Electron temperature profile and density profile is obtained by means of ECE (through a 2mm scanning heterodyne receiver) and a 5-channel HCN interferometer, respectively. As we know, the efficiency of the current drive and the ion heating depends on the plasma electron density in the experiments on tokamak. When electron density is lower then $1.5 \times 10^{13} cm^{-3}$, higher efficiency of current drive have been obtained and the particle confinement have been improved [1]in our tokamak. The current driven by the lower hybrid wave decreases gradually with rising of the electron density. In general, when n_e is higher than $2.5 \times 10^{13} cm^{-3}$, the current can not be driven by lower hybrid wave. The effect of ion heating can be observed when electron density is higher than $1.5 \times 10^{13} cm^{-3}$. Two different features of ion heating have been observed at $n_e \approx 2 \times 10^{13} cm^{-3}$ and n_e>$3 \times 10^{13} cm^{-3}$, respectively. The bulk ion heating and fast ion generating appear under the different conditions. To understand the heating mechanism, the relationship between the lower hybrid heating efficiency and plasma parameters, especially the electron temperature has been investigated. The main experimental results are as follows.

At the modest density($\approx 2 \times 10^{13} cm^{-3}$), ion temperature can increase about 200eV. The main parameters of shot 4988 are shown in Fig.1. The LHW is launched from 360ms with about 400kW power. During LHH, the electron density increases from $2 \times 10^{13} cm^{-3}$ to $3 \times 10^{13} cm^{-3}$, which is related with the improved particle confinement according to previous

investigation[1]. An obvious drop of loop voltage is observed during LHH. In this process, the plasma current keeps constant through feed back control. From Fig.1(c) and (d), we can see that the intensity of soft x-ray and electron cyclotron emission increases greatly. Because in this case, the impurity level does not changed, so the former indicates increases of electron temperature and electron density and the latter indicates the fast electron radiation. These mean that when LHW is launched in plasma, both bulk and fast electrons obtain energy from LHW. At the same time, the ion temperature increases from 600eV to 800eV in 50 ms. Maxwellian ion energy spectra can be observed under this condition, as shown in fig.2. It shows that the bulk ion temperature increase.
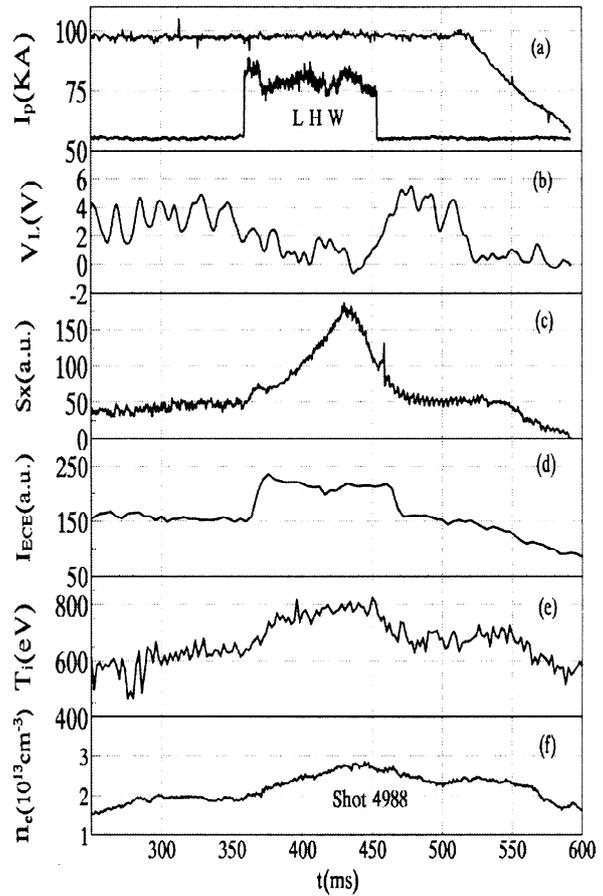

Fig.1 Evolution of the main plasma parameters of shot 4988 (a) plasma current and LHW (b) Loop Voltage (c) soft X-ray (d)ECE (e) ion temperature (f) electron density

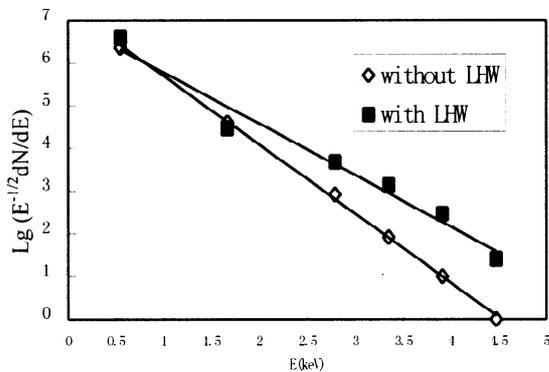In our preliminary experiments, the optimum bulk ion heating condition

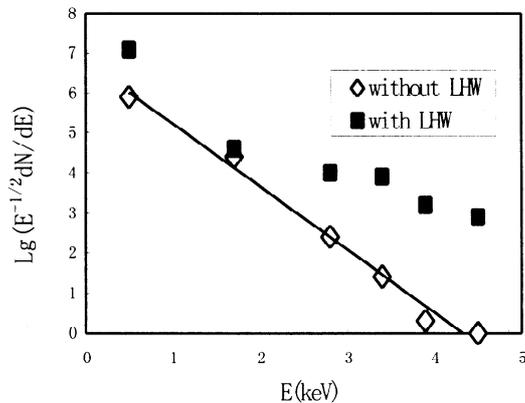Fig.2 CX spectra with and without LHW in modest density

Fig.3 CX spectra with and without LHW in higher density

seems difficult to be obtained, because some other factors, for example the impurity, may influence the heating effect significantly.

The feature of the ion heating in shot 4996 is different with that in shot 4988. In this discharge, the electron density is higher than $4 \times 10^{13} cm^{-3}$, which retains constant during LHH. The plasma current $I_p = 100kA$, toroidal magnetic field $B_T = 2.3T$ and the power of LHW is 400kW. Bi-Maxwellian ion energy spectra have been observed, as shown in Fig.3. From the ion energy spectrum, we can see that the ions with energy more than 3keV increase greatly and the ion flux with lower energy almost does not change. It should be noted that the rising time of the ion flux of every CX channels is very short (less then 5 ms). Fig.4 shows the time evolutions of the neutron flux with 3keV in shot 4996 and in shot 4988. The quick rising time means that the ions interact with wave directly. In these cases, electron temperature

Fig.4 Evolution of neutron flux (3keV) during LHW
(a) modest density (b) higher density

(from the measurement of the soft X-ray and ECE) does not increase. Under these conditions, the relationship between the efficiency of the fast ion generation and plasma parameters has been investigated. The fast ion heating occurs when plasma density is higher than $2.5 \times 10^{13} cm^{-3}$. When electron density is fixed, the increment of the fast ion temperature from ohmic stage to LHH stage decreases with the increasing of electron temperature. From our experimental data, the increment of the fast ion temperature seams to depend on the Te/ne. According to the reference [2], the threshold power of parameter decay instability is proportional to Te/ne, for fixed toroidal magnetic field B_T, and frequency of LHW f_{LH} .Fig.5 show the relationship between increment of fast ion temperature $\triangle T_{fi}$ and $n_e P_{LH}/Te$ .We can see that when the power threshold of parameter decay instability is lower (compare with LHW power), $\triangle T_{fi}$ is higher. That means the effect of the fast ion heating may depend on the condition of parameter decay instability in the center plasma.
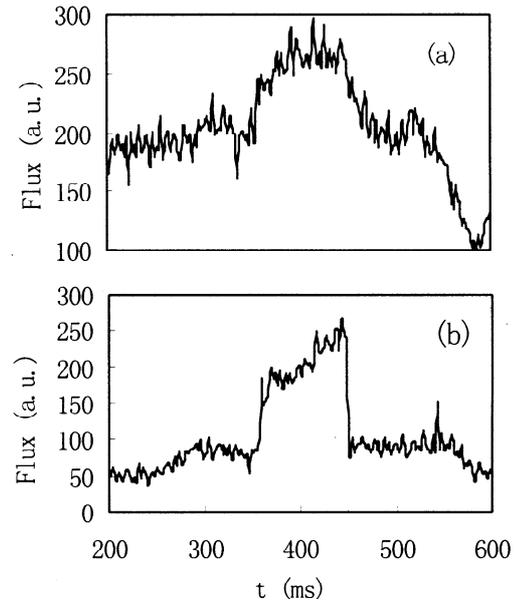
According to the phenomena mentioned above, we conclude that the ions can be heated by LHW in the modest density with the following features: 1) the ion energy distribution is Maxwellian; 2) the ion heating occurs with the current drive or electron heating, simultaneously; 3) during LHW, the rising time
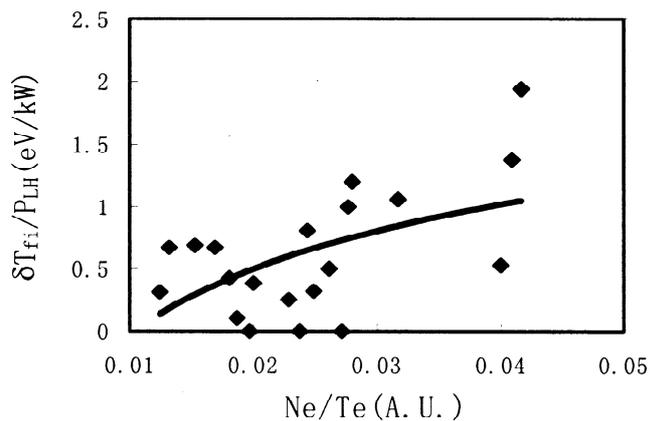

Fig. 5 Relationship between $\delta Tfi/PLH$ and Ne/Te

of ion temperature is about several ten milliseconds. From these features, we think that the pure ion heating seems to depend on the heating of electrons, instead of interacting with the LHW directly. Under this condition, the velocity of the wave may become lower gradually, due to increasing of plasma density and some bulk electrons can be heated in the improved confinement condition. In consequence of collisions with electrons, the bulk ions can acquire energy from electrons. In our experiments the increment of ion temperature is about 200 eV. In higher density, the other features appears as following: 1) the ion energy spectra are bi-Maxwellian; 2) the flux of the higher energy ions increases abruptly when LHW is launched; 3) when ion heating occurs, the electron temperature is not increased; 4) the effect of the heating is proportional to $n_e P_{LH}/T_{e.}$ It is clear that the ions with higher energy interact with the wave directly. The ion heating mechanism seems to relate to parameter decay threshold power as mentioned in reference [3]. In this case the fast ion tail is produced mainly.

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