LETTER

Experimental observation of ion heating by mode-converted ion Bernstein waves in tokamak plasmas

To cite this article: X.J. Zhang et al 2012 Nucl. Fusion 52 082003

View the article online for updates and enhancements.

Related content

- Observation of ion-cyclotron-frequency mode conversion plasma rotation on HT-7
  W Y Zhang, Y D Li, X J Zhang et al.

- ICRF mode conversion flow drive on Alcator C-Mod
  Y. Lin, J.E. Rice, S.J. Wukitch et al.

- Ion cyclotron range of frequency mode conversion flow drive in D(3He) plasmas on JET
  Y Lin, P Mantica, T Hellsten et al.

Recent citations

- Progress on ion cyclotron range of frequencies heating physics and technology in support of the International Tokamak Experimental Reactor
  J. R. Wilson and P. T. Bonoli

- Observation of Electron Energy Pinch in HT-7 ICRF Heated Plasmas
  Ding Siye et al

- Second-order radio frequency kinetic theory revisited: Resolving inconsistency with conventional fluid theory
  Jiale Chen and Zhe Gao
LETTER

Experimental observation of ion heating by mode-converted ion Bernstein waves in tokamak plasmas

X.J. Zhang\textsuperscript{1,5}, Y.P. Zhao\textsuperscript{1}, B.N. Wan\textsuperscript{1}, X.Z. Gong\textsuperscript{1}, Y. Lin\textsuperscript{2}, W.Y. Zhang\textsuperscript{1}, Y.Z. Mao\textsuperscript{1}, C.M. Qin\textsuperscript{1}, S. Yuan\textsuperscript{1}, X. Deng\textsuperscript{1}, L. Wang\textsuperscript{1}, S.Q. Ju\textsuperscript{1}, Y. Chen\textsuperscript{1}, Y.D. Li\textsuperscript{1}, J.G. Li\textsuperscript{1}, J.M. Noterdaeme\textsuperscript{3,4} and S.J. Wukitch\textsuperscript{2}

\textsuperscript{1} Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, People’s Republic of China
\textsuperscript{2} MIT Plasma Science and Fusion Center, Cambridge, MA 02139, USA
\textsuperscript{3} Max Planck Institute for Plasma Physics, D-85748 Garching, Germany
\textsuperscript{4} Electrical Energy, Systems and Automation Department, Gent University, B-9000 Gent, Belgium

E-mail: xjzhang@ipp.ac.cn

Received 23 February 2012, accepted for publication 17 July 2012
Published 1 August 2012
Online at stacks.iop.org/NF/52/082003

Abstract

We report the experimental observation of ion heating by the mode-converted ion Bernstein waves (MC IBWs) in tokamak plasmas. The MC IBW is created from the fast waves launched from the high-field-side antenna in the HT-7 tokamak in plasmas consisting of deuterium majority, hydrogen minority and \textsuperscript{7}Li ions. Experimental evidence and numerical simulation show that the interaction between the MC IBW and \textsuperscript{7}Li ions at the first ion-cyclotron harmonic resonance of \textsuperscript{7}Li (i.e. $\omega = 2\Omega_{\text{1-7Li}}$) is the main mechanism for radio-frequency power deposition. By comparing with previous experiments of direct-launch IBW flow drive on tokamaks and existing theories, we hypothesize that this MC IBW and \textsuperscript{7}Li interaction also leads to the observed flow drive effect.

(Some figures may appear in colour only in the online journal)
have peak power at toroidal numbers $n_{\phi} = \pm 6$, corresponding to $k_{\parallel} \sim \pm 5 \text{ m}^{-1}$. Lithium powder (mainly $^7\text{Li}$) has been used extensively to condition the walls of the tokamak to control impurities and also reduce the hydrogen (H) level [16]. Spectroscopic measurements indicated that the typical level of $^7\text{Li}$ ions in the plasmas was $n_{\text{Li}}/n_e = 0.5\%$–$1.0\%$. As a result, the typical plasma composition in the experiment was a mixture of deuterium (D), H and $^7\text{Li}$. Figure 1 shows the cross section of HT-7 together with the location of the ICRF antenna, H cyclotron layers, MC layer (D-H hybrid layer) and the first harmonic $^7\text{Li}$ IC layer in the experiment for $B_0 = 2.0 \text{T}$ and $n_{\text{Li}}/n_e = 15\%$.

Plasma rotation correlated with the launched rf power has been observed in these D-H-$^7\text{Li}$ plasmas. The flow (rotation) velocity $V_\theta$ is inferred from the Doppler shift in the turbulence spectra measured by a collective Thomson scattering system using a CW CO$_2$ laser [17]. As shown in figure 2, we plot the traces of the rotation with that from the ohmic period subtracted, $\Delta V_\theta$, in two regions, $0 < r/a < 0.4$ and $0.3 < r/a < 0.7$. A significant change in $\Delta V_\theta$ is clearly shown following the application of the ICRF power. The opposite directions of $\Delta V_\theta$ in the two spatial regions suggest that the application of ICRF power creates a dipolar structure in the poloidal plasma rotation. The magnitude of the rotation is also larger at a higher rf power. The two-dimensional full wave code TORIC [18, 19] has been used to model the ICRF physics in these plasmas and to determine the power absorption via different mechanisms. In TORIC simulations, the impurity lithium ion was taken into account. Energy exchange between plasma particles was not taken into account. The TORIC simulation results [17] show that the interaction between the MC IBW and $^7\text{Li}$ ions at the first ion-cyclotron harmonic resonance of $^7\text{Li}$ (i.e. $\omega = 2\Omega_{\text{L},-7}$) is the main mechanism for rf power deposition.

To illustrate the detailed wave–particle physics, in figure 3 we plot the 2D contours of the electric field from the TORIC simulation with $n_{\phi} = +6$. The $E$ field is decomposed to $E^+$, $E^-$ and $E_\parallel$, i.e. left-handed polarization, right-handed polarization, and parallel to $B$. In figure 3(a), over the large structure of fast waves, the fine structure of the shorter wavelength MC waves is shown in $E^+$ contours. Whereas the fast wave has near to zero $E_\parallel$, the MC IBW is clearly shown in figure 3(b) on the HFS of the MC layer and the MC ICW on the LFS of the MC layer. While propagating towards the HFS, the amplitude of the MC IBW has a steep drop at the $\omega = 2\Omega_{\text{L},-7}$ layer, indicating a strong local absorption. The power deposition is shown in figure 4. The total power to the electrons is dominated by the MC IBW and ICW as shown in figure 4(a). In figure 4(b), the power to $^7\text{Li}$ via the interaction of the MC IBW and $^7\text{Li}$ ions is shown to be strongly peaked and localized near the resonance layer. The total power to $^7\text{Li}$ ions is similar to the total power to electrons.

To experimentally verify the MC IBW and $^7\text{Li}$ ions interaction is not straightforward. In the following, we show this from the response of the neutron rate versus RF power and versus a magnetic field scan. In figure 5, traces of two discharges at two different ICRF power levels are compared. The plasmas have $B_0 = 2.0 \text{T}$, $X_{\text{MC}} = 2 \text{ cm}$ and the $^7\text{Li}$ first harmonic layer at $X_{\text{Li},-7} = -3 \text{ cm}$, where $X$ is defined as the distance to the magnetic axis, $X = R - R_0$. The fusion neutron rate on both plasmas increases immediately (in a time scale of less than 20 ms) after the ICRF power is applied. Because the plasma density actually decreases slightly due to the ICRF density pump-out effect, the increase in neutron rate indicates either an increase in deuterium ion temperature ($T_D$) or the generation of energetic D ions. In these plasmas at $T_{\text{e0}} \sim 1.5 \text{ keV}$, the electron–ion heat exchange time is about 300 ms [20], an order of magnitude longer than the observed neutron rate rising time; therefore, the direct electron heating, e.g. from the MC IBW and ICW Landau damping, cannot explain the fast rise of the neutron rate.

Harmonic D heating and the collisional exchange between the hot H ions (due to H minority absorption) and bulk D ions could cause fast neutron rise, but this is shown not to be the case. In figure 6, we show discharges at three

\[ \omega = \Omega_{\text{H}} \]

\[ \omega = 2\Omega_{\text{H}} \]

\[ \omega = 2\Omega_{\text{L},-7} \]

\[ \omega = 2\Omega_{\text{L},-7} \]

\[ \omega = 2\Omega_{\text{L},-7} \]

\[ \omega = 2\Omega_{\text{L},-7} \]

\[ \omega = 2\Omega_{\text{L},-7} \]

\[ \omega = 2\Omega_{\text{L},-7} \]
different magnetic fields while other parameters are similar. Significantly different neutron rates have been observed. At \( B_{t0} = 1.73 \) T, where \( X_{17} = -20 \) cm (nearly out of the plasma) and \( X_H = -2 \) cm, the neutron signal is barely above the diagnostic sensitivity even though the H IC resonance layer (same as the first harmonic D IC layer) is located near the magnetic axis. This observation suggests that the harmonic D heating and H minority absorption are very weak, thus we can exclude the possible contribution of fast D ions from \( \omega = 2\Omega_D \) heating and \( T_D \) rise from \( \omega = \Omega_{17} \) heating. On the other hand, at \( B_{t0} = 1.9 \) T where \( X_{17} = -7 \) cm, \( X_{MC} = -3 \) cm, \( X_H = 10 \) cm and \( B_{t0} = 2.0 \) T where \( X_{17} = -3 \) cm, \( X_{MC} = 2 \) cm and \( X_H = 16 \) cm, high neutron signals have been observed throughout the entire ICRF phase. Note that the ion–ion heat exchange time is in the order of \( \sim 2 \) ms, shorter than the observed neutron rising time. Therefore, an increase
in $T_D$ due to interaction with rf directly heated $^7$Li ions would explain the fast rising time of the neutron signals. The level of the neutron rate versus $B$ field is also consistent with the percentage of rf power absorbed by the $^7$Li ions calculated from the TORIC simulation, i.e. 5%, 45% and 30%, respectively, for $B_{0\theta} = 1.73$ T, 1.92 T and 2.0 T. Extensive modelling and experimental evidence leads us to conclude that a significant amount of the MC IBW power is absorbed by $^7$Li ions at $\omega = 2\Omega_{\perp,7}$ in our ICRF-heated experiments on HT-7, and then the collisional exchange between the hot $^7$Li ions and bulk D ions increases $T_D$, which causes a quick and significant rise in the neutron rate.

The interaction of the MC IBW and $^7$Li ions at the fundamental $^7$Li IC resonance ($\omega = \Omega_{\perp,7}$) has been inferred in D (T) experiments in TFTR [21]. In [3], the absorption of the MC IBW at the $\omega = 2\Omega_T$ was proposed for JET and ITER D–T experiments, and this heating scheme was assessed via simulation, including using TORIC. The HFS launch of the fast waves on HT-7 helps increase the mode conversion efficiency. In typical LFS launch, the fast waves would have to tunnel through the left-hand cutoff, $n_{\perp,7}^2 = L$, before reaching the MC layer, $n_{\perp,7}^2 = S$, where $L$ and $S$ are the standard Stix notations [22]. In HFS launch, the fast waves would encounter the MC layer before they are reflected from the left-hand cutoff. As suggested in [23, 24], up to 100% of the fast waves can be mode converted in this HFS launch scenario. In the MC heating experiments reported from other tokamaks, for example, [25–27], the MC IBW is strongly damped to the electrons near the MC layer. In our experiment with somewhat lower $T_e$ ($\sim 0.7$ keV) and smaller $k_z$, the phase velocity of the MC IBW in the vicinity of the MC layer is approximately thrice the electron thermal velocity, resulting in a rather weak Landau damping on electrons (e.g. figure 4(a)). Therefore, the MC IBW can propagate up to $\omega = 2\Omega_{\perp,7}$ layer without significant loss of wave power to electrons before being mostly absorbed by the $^7$Li ions (figure 4(b)).

Usually, the MC IBW propagates on the HFS of the ion–ion hybrid resonance and is absorbed by electron Landau damping and magnetic pumping [25–27]. By themselves, these mechanisms do not lead to poloidal flow [28]. However, interaction between the lithium ions and the mode-converted IBW leads to wave damping, which is ion-cyclotron damping of MC IBW. The resulting poloidal forces in this layer can drive sheared poloidal flow, as suggested in [28, 29].

In summary, the flow drive effect has been observed in ICRF-heated tokamak plasmas where the MC IBW is mostly absorbed by ions. By carefully selecting the rf frequency, $B$ field, antenna phase, species mix, and other plasma parameters, such a scenario might be applicable in future burning plasma experiments equipped with ICRF heating, such as ITER and IGNITOR [3, 30], possibly for ion heating and plasma flow control.

Acknowledgments

The authors would like to acknowledge the support of the HT-7 operation and diagnostics group and to thank Drs C. Castaldo and Y. Kazakov for helpful comments and R. Bilato for the TORIC code. This work was supported by the ITER Relevant Foundation in China (grant no 2010GB110000). This work was also supported by the National Natural Science Foundation of China under grant no 10725523 and no 10721505 and no 11105179 and no 10928509 and no 10990212. This work was supported partly by the Knowledge Innovation Program of the Chinese Academy of Sciences no Y05FCQ0126.

References