Letter

Thermal ions heat transport induced by reversed shear Alfvén eigenmode on the HL-2A tokamak

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Abstract

Experimental investigations of thermal ions heat transport induced by reversed shear Alfvén eigenmodes (RSAEs) have been carried out on the HL-2A tokamak. It is found that the RSAEs are driven unstable by passing particles during the second half of sawtooth periods, and can not only degrade the bremsstrahlung radiations, but also cause obvious reduction of the ion temperature in the core plasma. Interestingly, the RSAEs excited by energetic ions can resonant with the thermal ions, and then lead to a heat transport process. Statistical results suggest there is a quadratic dependence between thermal ion heat flux perturbation and mode amplitude, which indicates a diffusive mechanism of plasma transport and is well explained by the theoretical interpretations derived from quasi-linear transport theory.

Keywords: thermal ions, heat transport, reversed shear Alfvén eigenmode

(Some figures may appear in colour only in the online journal)
ions. Even though it is claimed that there is a dominant interaction of multiple SAWs with thermal ions in high-temperature fusion plasmas [12], and the ion temperatures decline during multi-scale interactions among kink/tearing modes and high frequency fluctuations [13]. Since the thermal ions are the main fuel for fusion action and SAWs fluctuation are easily driven unstable in the future burning plasma [14–16]. Further understanding of the interaction among thermal ions and Alfven waves is urgently needed. In this letter, we will present the observations of thermal ion heat transport induced by the energetic ions driven RSAEs, which is a typical discrete SAW instability in the reverse magnetic shear plasma and characterized by frequency sweeping slowly due to moderate change of minimum safety factors [17–23]. The RSAEs lead to a diffusive transport, i.e. \( \delta q_i/n_i \propto (\delta B_\theta)^2 \), where \( \delta q_i/n_i \) is ion heat flux perturbation normalized by the ion density and \( \delta B_\theta \) represents amplitude of magnetic fluctuation induced by RSAEs at the edge. The experimental evidences are well explained by the quasi-linear transport theory [24], which predicts the ion heat flux has a quadratic dependence on electrostatic or magnetic potential of RSAEs.

The experiments are performed in deuterium plasmas on the HL-2A tokamak with major/minor radius \( R/\alpha = 1.65\ m/0.40\ m \). Multiple advanced plasma diagnosis are involved in the experimental campaign. The Mirnov coils are powerful tools for the detection of magnetic fluctuation and mode numbers. There are 32 channels for the charge exchange recombination spectroscopy (CXRS), it can achieve spatial/temporal resolution of 1 cm/12.5 ms and will provide information of ion temperature and toroidal rotation frequency [25]. The electron cyclotron emission (ECE) radiometer [26, 27] and frequency modulated continuous wave (FMCW) reflectometer [28] contribute to electron temperature and density profile measurement, respectively. Figure 1 shows typical histories of discharge parameters during shot 24 986 and 22 484. The plasma currents range \( I_p = 140 – 170\ kA \) and toroidal magnetic fields are around \( B_t = 1.3 – 1.4\ T \). The line-averaged electron densities obtained from far infrared rays laser interferometer display obvious sawtooth activities during tangentially injected neutral beam with powers of 750 kW.

The spectrogram of Mirnov coil signal during 560 – 730 ms of shot 24 986 is given in figure 2. The modes with frequency quickly down-sweeping from 150 kHz to 110 kHz are regarded as \( n = 3 \) TAEs. There are internal kink modes, which appear just before the sawtooth collapse. The modes appearing at the second half of sawtooth are RSAEs with poloidal and toroidal mode numbers of \( m/n = 2/2 \) or 3/3. Note that low frequency modes (LFMs) always grow simultaneously with the two famous discrete shear Alfven wave spectra and there may be non-linear wave–wave resonance among the three modes. Soft-x signal has been plotted as the dark curve. Interestingly, bremsstrahlung radiations fall down when the RSAEs are driven unstable. The phenomenon can also reproduce when RSAEs coexist with TAEs. It is worthy pointing out that bremsstrahlung radiations origin from collisions between thermal ions and electrons, the soft-x signal change may indicate redistribution of thermal particles.

Another typical case can be seen in figure 3. The RSAE mode frequencies slowly sweep up and exhibit chirping behaviours. The grow rates of non-linear RSAEs can be estimated from \( \omega = \omega_0 \pm \gamma_i \sqrt{\gamma_d} \). Here \( \omega \) and \( \omega_0 \) are temporal mode frequency and the counterpart at pitch fork bifurcation. The \( \gamma_l \) and \( \gamma_d \) are the kinetic drive and intrinsic damping rate from background plasma, the two factors are comparable for near marginal stabilities. Plus and minus represents the mode chirping up and chirping down, respectively. Figure 4 presents a close-up of figure 3(c). To evaluate the drive and damping, two special cases have been selected and marked out in figure 4(b). For the case I, the kinetic drive and intrinsic damping rate are around \( \gamma_l \approx \gamma_d = 9.2 \times 10^3\ s^{-1} \), here the blue circles are experimental frequency and the dotted curve is numerical fitting result based on the given formula. But for the case II, i.e. when RSAEs appear together with TAEs, the upper and down branches evolve with different drives and damps. The upper branch is fitted with \( \omega = \omega_0 + \gamma_l \sqrt{\gamma_d} \) while the down-chirping branch with \( \omega = \omega_0 - \gamma_l \sqrt{\gamma_d} \), shown as the red and dark curves, respectively. The fitting results suggest that drive and damping of the upper branch is about \( 20 \times 10^3\ s^{-1} \), which...
Figure 3. The temporal electron temperatures detected by electron cyclotron emission (ECE) radiometer at locations of (a) \( \rho = 0.08 \) and (b) \( \rho = 0.22 \). (c) Magnetic signal filtered by the numerical filter with frequency of \( 65 - 85 \) kHz. (d) Ion temperatures obtained from charge exchange recombination spectroscopy (CXRS) at multiple positions. (e) Spectrogram of Mirnov coil signal for shot 22 484, the ion temperature \((x100)\) at \( \rho = 0.04 \) and the corresponding fitting curve are also plotted.

Figure 4. The RSAEs pitch forks: a close up of figure 3(e). The grow rates of non-linear RSAEs have been estimated from formula of \( \omega = \omega_0 \pm \gamma l \sqrt{\gamma d t} \).

is twice as much as \( 8.7 \times 10^3 \) s\(^{-1} \) of the down-chirping counterpart. Figure 3 also reveals the RSAEs play important roles in the discharge parameter evolutions.

The electron temperatures detected by ECE system at different locations (\( \rho = 0.08 \) and 0.22) are arranged at the first two subgraphs. The electron temperature increases gradually and then comes into flat-top state during a sawtooth period in figure 3(a) while figure 3(b) presents a opposite trend of sawtooth activity. Magnetic signal is filtered by the numerical filter with frequency of \( 65 - 85 \) kHz and plotted in figure 3(c). The fluctuation amplitudes induced by RSAEs are about \( |\delta B_\theta| = 0.4 - 1.0 \mu T \). The ion temperatures (\( T_i \)) at multiple positions are provided by CXRS, shown as figure 3(d). The \( T_i \) has different evolutions from electron temperature during a sawtooth period. In core region, \( T_i \) goes up firstly and then declines, but there is no flat-top state. Though poor time resolution of 12.5 ms, the sawtooth can also be observed by the CXRS system and \( T_i \) falling down to minimum in core area is expected when the sawtooth collapses. To make the temporal evolution more clear, three minimums (green prisms) are artificially added to the ion temperature \((x100)\) at \( \rho = 0.04 \). Numerical fitting is performed, which is shown as the dark curve in figure 3(e), and good fitting degree can be obtained. Surprisingly, \( T_i \) declines immediately when the RSAEs are driven unstable.

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The discharge parameters at 600 ms and 612.5 ms are exhibited at figure 5. Electron densities given by FMCW reflectometer show a slight difference and the temperatures keep almost unchanged because the two moments appear at the flat-top of sawtooth period. However, the \( T_i \) and rotation frequency are quite different in the region of \( \rho < 0.4 \). At the magnetic axis, \( T_i(0) \) is about 1.2 keV at 600 ms and it falls down to 0.8 keV at 612.5 ms. Obvious decline can also be seen at the rotation frequencies. The SAW fluctuation seem to mainly affect the thermal ions rather than electrons. Actually, the resonance condition between RSAEs and thermal ions can be described as \( \omega_0 - k_\parallel |V_\parallel| - \omega_\eta = 0 \), where \( l \) is an integer, \( \omega_0 \) and \( \omega_\eta \) are the RSAE frequency and thermal ion transit frequency. In the experiments, \( \omega_0 \) ranges \( 4.4 - 6.28 \times 10^5 \) rad/s when the rotation frequency is removed and \( \omega_\eta = \sqrt{2T_i/m_i/qR} \approx 1.65 \times 10^5 \) rad/s. Besides, the \( k_\parallel = (n - m/q)n R / |R| \approx 0.024 \) m\(^{-1} \) with \( m/n = 2/2 \) and

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Conclusions can be drawn that the wave-particle resonance condition among RSAEs and thermal ions is satisfied. However, the RSAEs are driven by the energetic ions, but not by thermal ions. On one hand, the condition for RSAE driven unstable by thermal ions require strong ion temperature gradient as well as high toroidal mode number, to have the thermal ion diamagnetic drift frequency higher than RSAE frequency. But these two conditions are not satisfied in the present experiment. On the other hand, the high energy tail of thermal ions distribution, can resonant with RSAE, and lead to thermal ion heat/particle transport. In this case, since the RSAEs are mainly driven by energetic particles, the resonant thermal ions can be viewed as ‘passive’ test particles. Besides, the thermal ions are thought to be critical to the destabilization of Alfvénic modes with high toroidal mode numbers of n ≥ 10, but it will suppress the low n modes due to a large thermal ion Landau damping contribution [12]. The T_e declines obviously in the core region but increase at the edge during the RSAEs excitation, which indicates the modes contributes mainly to thermal transport rather than heating. To confirm the conclusion, a comparison between the change rate of energy and angular momentum induced by the RSAEs has been made, and it is given as \( \frac{\dot{E}}{\dot{P}_r/P_\phi} = \frac{E}{P_\phi} \). According to the extended phase space Hamiltonian, one has \( \dot{E} = \omega P_\phi / n \). The detailed expressions of energy E and angular momentum P_\phi are given by (7) and we can finally arrive at \( \frac{\dot{E}}{P_\phi} < \frac{2 \kappa}{n} = 0.45 - 0.64 \) in the experiment, which suggests that the angular momentum changes more quickly than energy, i.e. the thermal transport plays a dominant role during RSAEs evolution. Recently, gyrokinetic simulations have found that the ion heat flux is dominated by the Alfvén eigenmode and its main harmonics in the presence of turbulence [29], which also reveals the fact that Alfvénic fluctuation may lead to thermal ions transport. It is worth pointing out that the most unstable mode numbers are higher in the future large fusion device while frequencies of Alfvénic modes range are almost the same as the present observations, therefore, the thermal transports are expected to be much more important than that on medium-sized HL-2A tokamak. Last but not least, the RSAEs can also induce momentum transport, depending on the parallel wave-number asymmetry with respect to the mode structure [30]. Spatial channelling of momentum mainly affect the sheared plasma rotation [31]. However, due to the absence and limitation of plasma diagnosis with high temporal-spatial resolution during the last experimental campaign, we can not provide convincing evidence of RSAE induced momentum transport. But there are no doubts that it is an important topic in energetic particle physics, and we will try to explore in future work.

In order to examine in depth the dynamic behaviour of ion heat transport during the core T_e declining, a transient response analysis is carried out. The ion heat flux perturbation \( \delta q_i \) can be evaluated by deforming the energy conservation equation for ion perturbation [32–34]:

\[
\delta q_i(r,t) = -\frac{1}{r} \int_0^r \hat{\delta} T_i(r,t) \frac{\partial}{\partial \rho} \rho \, dp. \tag{1}
\]

Here, \( n_i \) is the ion density and assumed as \( n_i = n_\alpha \delta T_i(r,t) \) representing ion temperature perturbation induced by the RSAEs, keV as unit. In arriving at the above equation, the terms related
to density perturbation, and perturbed source terms of the heat and particles are ignored in the energy conservation equation. It is because the density is kept almost unchanged and there are no particle injections or modulated auxiliary heating during the shear Alfvén wave activity. Figure 5 shows the relation of ion heat flux perturbation at \( \rho = 0.04 \) normalized by the ion density \( \langle \delta q_i/n_i \rangle \) at amplitude of magnetic fluctuation \( |\delta B_θ|\). The linear and quadratic fitting results have been plotted as the blue dotted line and red curve, respectively. The result reveals a quadratic dependence between \( q_i \) and \( \delta B_θ \).

For the RSAEs with SAW polarization, we have \( \delta \phi_k \sim \delta \psi_k \), \( J_k = J_0(k_\perp \rho) \) with \( J_0 \) being the Bessel function of zero index, \( \rho = V_\perp/\Omega_e \), \( \Omega_e \) is the cyclotron frequency. [...] is the surface average and \( \delta H_k \) is the nonadiabatic distribution function, which can be derived from linear gyrokinetic equation [36]:

\[
(-i\omega + V_\parallel \partial_\parallel + i\omega_\parallel)\delta H_k = -i\omega \frac{Q_{F0}}{m} J_0 \delta L_k,
\]

(3)

with \( Q_{F0} = (\omega_\parallel \partial_\parallel - \omega_\parallel) F_0 \), \( \omega_\parallel F_0 = \frac{1}{4} k_\parallel \cdot \mathbf{b} \times \nabla F_0 \) and \( \varepsilon = V_\parallel^2/2 \). \( \omega_\parallel = (V_\parallel^2 + 2V_\perp^2)/(2\Omega, R) \) is the magnetic drift frequency. For thermal ions, one typically has \( \omega_\parallel > \omega_{RSAE} \) while \( \omega_\parallel < \omega_{RSAE} \) for energetic ions. For RSAEs induced thermal ion diffusive transport, the dominant contribution comes from \( \omega_\parallel \), while \( \omega_\parallel \partial_\parallel \) term is usually corresponding to a convection process. The thermal ion nonadiabatic response to RSAEs can be written as:

\[
\delta H_k = -\frac{e}{m} Q_{F0} \omega_\parallel \delta L_k \sum_i \left( \frac{J_i(\lambda_d e^{i\omega_\parallel})}{\omega_\parallel - k_\parallel V_\parallel - i\omega_i} \right),
\]

(4)

with \( \lambda_d = \lambda_d \sin \theta \), \( \lambda_d = k_\perp \rho_d \), and \( \rho_d = (V_\perp^2 + 2V_\parallel^2)^{1/2} \) is the magnetic bounce orbit width. Substituting into the quasi-linear transport equation, we then have:

\[
\partial_\parallel F_0 = -\frac{c}{B_0} \sum_{k'=-k} \mathbf{b} \cdot \mathbf{k}' \times \mathbf{k}' J_k \delta L_k \delta H_k \sum_{k'=0} \left( \frac{J_i(\lambda_d e^{i\omega_\parallel})}{\omega_\parallel - k_\parallel V_\parallel - i\omega_i} \right).
\]

(5)

Note that \( \frac{1}{\omega_\parallel - k_\parallel V_\parallel} - \frac{1}{\omega_\parallel - k_\parallel V_\parallel} = \frac{-2i\pi \delta(\omega_\parallel - k_\parallel V_\parallel)}{\omega_\parallel} \) and \( Q_{F0} \approx \frac{-\omega_\parallel}{\omega_\parallel} - \frac{1}{\omega_\parallel} \). Further, \( \delta \phi \sim \frac{1}{\omega_\parallel} \), so the equation above can be rewritten as:

\[
\partial_\parallel F_0 = 2\pi \frac{c}{B_0} \frac{e}{\Omega_e} \sum_i \frac{F_i}{\omega_i} \delta(\lambda_d) \frac{\partial}{\partial \omega_\parallel} \delta(\omega_\parallel - k_\parallel V_\parallel - i\omega_i) \frac{\omega_i}{\omega_\parallel} \frac{\partial}{\partial \omega_\parallel} F_0.
\]

(6)

Finally, the RSAE induced ion heat flux can be described as:

\[
q_i = 2\pi \frac{c}{B_0} \frac{e}{\Omega_e} \sum_i \frac{F_i}{\omega_i} \delta(\lambda_d) \frac{\partial}{\partial \omega_\parallel} \delta(\omega_\parallel - k_\parallel V_\parallel - i\omega_i) \frac{\partial}{\partial \omega_\parallel} F_0.
\]

(7)

Shown here, the ion heat flux induced by RSAEs closely relates to the gradient of equilibrium distribution function and the mode amplitude. The \( q_i \) is proportional to \( \frac{dF}{d\omega_\parallel} \) and it has a quadratic dependence on \( |\delta \phi_k| \), which is consistent with the sloping from experiment. However, it is quite difficult to make
a quantitative comparison between the experimental measurement and theoretical prediction. On one hand, the limitations of plasma diagnosis prevent us to obtain a relatively reliable gradients of equilibrium distribution function. On the other hand, the local amplitudes of RSAEs are unavailable in the core region. In this experiment, the local amplitudes is replaced by the edge magnetic fluctuation and only the ion heat flux perturbation is available. But experimental evidence of thermal ions heat transport induced by RSAEs with a diffusive mechanism qualitatively agrees with the theoretical explanation.

In summary, thermal ions heat transport induced by RSAEs has been investigated on the HL-2A tokamak. The RSAEs are driven by passing energetic ions and lead to a decline of soft-x signal and ion temperature. Analysis suggests that the RSAE-thermal ion resonance is possible in the HL-2A plasma. As a result, ion heat transport due to the core localized SAW fluctuation takes place. The ion heat flux perturbation shows a quadratic dependence on the magnetic amplitude. In other words, the RSAEs leads to plasma transport with a diffusive mechanism. The quasi-linear transport theory points out that the relation between ion heat flux and mode amplitude should be $q_i \propto |\delta \phi_i|^2$, which is qualitatively in accordance with experimental consequence. It should be pointed out that the thermal ions can exchange energy and momentum with RSAEs, but those particles are not the dominate factor for destabilization of reversed shear Alfvén eigenmodes. Finally, the results presented here may contribute to better understandings for the wave-particle interactions and subsequent energy or particle transport induced by energetic ions driven magneto-hydrodynamic instabilities in fusion devices.

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