OBSERVATION OF CORE ION ENERGY INCREASE CAUSED BY THE LANDAU DAMPING OF MHD WAVE IN THE PERIPHERY OF LHD PLASMA

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The increase of ion kinetic energy in the core due to the Landau and transit-time damping of energetic-particle driven MHD wave near the plasma periphery is observed in the Large Helical Device using 10kHz fast charge exchange spectroscopy[1] in which the time integration is shorter than the ion-ion collision time scale. This experiment demonstrates that the wave-particle interaction, such as Landau and transit-time damping of EP-driven MHD wave, can be a candidate for the ion heating scenario in the burning plasma, where no direct ion heating by alpha particles is expected.

In the burning plasma, the alpha particle energy is transferred to electrons, and the collision between electrons and ions heats bulk ions. Then the T_e/T_i ratio is expected to be larger than unity. However, a recent LHD experiment shows the appearance of the ion transport barrier (a drop of ion thermal diffusivity) with a lower T_e/T_i ratio below 0.75. (Similar results are reported in EAST experiments [2]). Therefore, the question is how to reduce T_e/T_i ratio below unity to sustain burning plasma in the hot ion mode. The heating scenario using wave-particle interaction, called alpha-channeling [3], is a promising technique. We directly observe the deformation of ion-velocity space from the Maxwell-Boltzmann distribution and collisionless energy transfer from waves excited by energetic particles to bulk ions via Landau and transit-time damping in LHD plasma [4,5]. A significant magnetic field perturbation at the onset of the MHD burst characterizes the discharge with transit-time damping. In contrast, the discharge with Landau damping is characterized by a MHD burst lasting more than 2 ms with frequency chirping down.

Figure 1 shows the ion velocity distribution parallel to magnetic field measured 0.1ms before and after the onset of the MHD burst measured with toroidal (nearly parallel to magnetic field) charge exchange spectroscopy. The MHD wave propagates in toroidal direction. Here, conditional averaging concerning the onset of ~ 150 MHD bursts is applied to improve the signal-to-noise ratio of the velocity distribution measured by one order of magnitude (the standard deviation of the data from the smoothed curve is reduced to 1% of the peak value). The distortion of the velocity distribution from the Maxwell distribution is seen only in the positive velocity, which is parallel to the propagation direction of the MHD wave. The measured ion velocity distribution (intensity) is well fitted by a Gaussian + derivative of a hyperbolic tangent function, as seen in Figure 1. The fitting residual $\delta f(v_{\parallel})$ (measured value – fitted value) is less than a few % of the peak. The magnitude of the first derivative of the velocity distribution, $|df(v_{\parallel})/dv_{\parallel}|$, is derived by taking the first derivative of the fitted curves. The drop of $|df(v_{\parallel})/dv_{\parallel}|$ at the mid-velocity of 200-300 km/s for 0.1ms after the onset of the MHD burst shows the partial flattening of the velocity distribution at the phase-velocity of the MHD wave evaluated from the frequency and toroidal mode number. This partial flattening of $f(v_{\parallel})$ is clear evidence of particle acceleration due to the transit-time or Landau damping and is most significant at r_{eff}/a_{99} = 0.79, where the MHD bursts occur. The partial flattening was not observed in the plasma core (r_{eff}/a_{99} = 0.55) and was less pronounced near the plasma periphery (r_{eff}/a_{99} = 0.97).

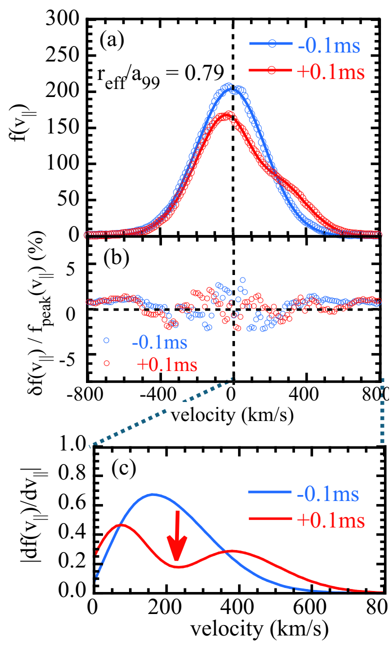

Fig.1. (a) Velocity distribution function f(v) measured with 10 kHz fast charge exchange spectroscopy (open circles) and fitted curve (lines), (b) fitting residual, $\delta f(v_{\parallel})$ and (c) first derivative of the fitted curve at normalized minor radius r_{eff}/a_{99} of 0.79 for 0.1ms before and after the onset of MHD burst.

It is essential to evaluate the kinetic energy of bulk plasma to evaluate the ion heating by transit-time and Landau damping. Here, the parallel and perpendicular kinetic energy $E_{\parallel}$ and $E_{\perp}$ are defined by integrating $v_{\parallel}^2 f(v_{\parallel})$ and $v_{\perp}^2 f(v_{\perp})$ in the velocity region from -700 to 700 km/s, and the magnitude is normalized by the average values before the onset of the MHD burst. Here, $v_{\perp}$ is the velocity distribution function perpendicular to the wave propagation direction measured with poloidal (nearly perpendicular to magnetic field) fast charge exchange spectroscopy. In this experiment, the kinetic energy is equivalent to the measure of temperature because the density is constant in time. Figure 2 shows the time evolution of magnetic field perturbation, contour of magnitude of first derivative of velocity distribution, $|df(v_{\parallel})/dv_{\parallel}|$, $|df(v_{\perp})/dv_{\perp}|$, parallel and perpendicular kinetic energy $E_{\parallel}$, $E_{\perp}$, at normalized minor radius r_{eff}/a_{99} of 0.55, 0.79, and 0.97 for the discharges with transit-time damping (left) and Landau damping (right) [6]. We found that the kinetic energy jumps to 1.2 times before the onset of the MHD burst, very rapidly within 0.1 ms. This timescale is much faster than the slowing down time of energetic particles and energy confinement time by $10^2 \sim 10^3$. This increase is not due to the fast radial propagation of hot plasma from the plasma core, such as a sawtooth crash. We do not see any drop of kinetic energy in the plasma core. The kinetic energy in the plasma periphery (r_{eff}/a_{99} = 0.97) decays after the onset of the MHD burst in the discharge with transit-time damping. However, higher kinetic energy is sustained during the MHD wave in the discharge with Landau damping. The kinetic energy and effective Doppler width in the core region (r_{eff}/a_{99} = 0.55) keeps increasing after the onset of the MHD burst. The increase of kinetic energy reaches up to 20% increase in the discharge Landau damping, where the MHD wave lasts for more than 2 ms.

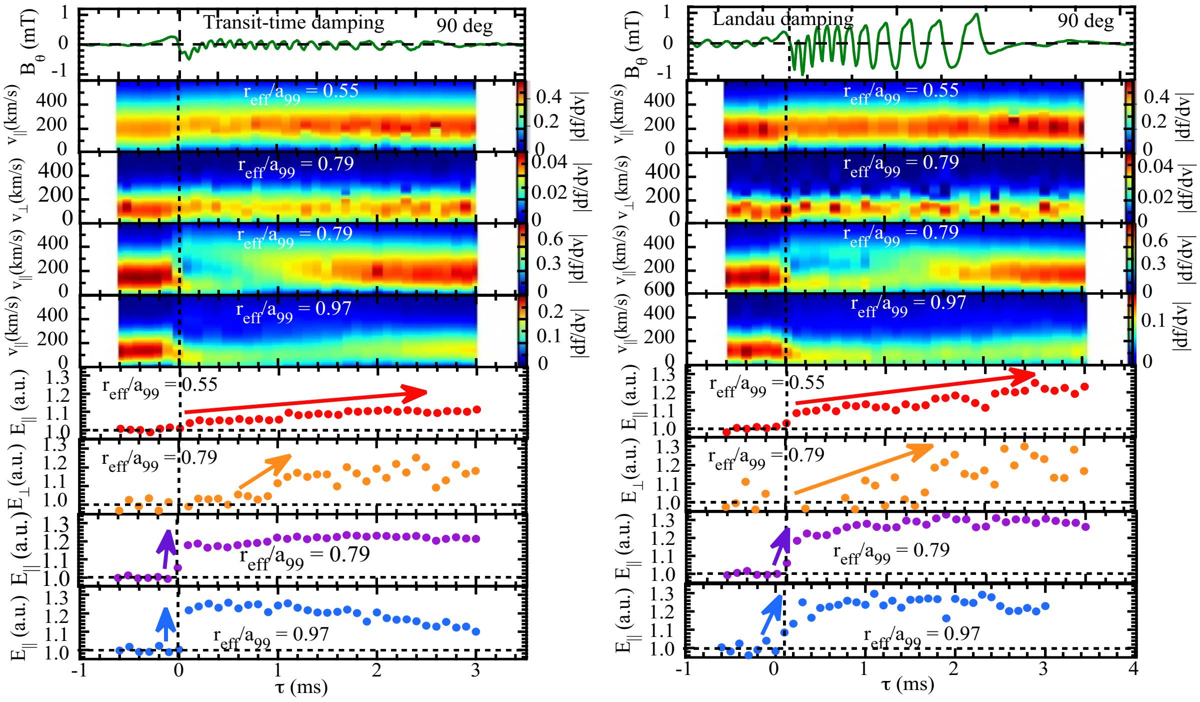

Fig.2. Time evolution of magnetic field perturbation, contour of magnitude of first derivative of velocity distribution, $|df(v_\parallel)/dv_\parallel|$, $|df(v_\perp)/dv_\perp|$, parallel and perpendicular kinetic energy $E_\parallel$, $E_\perp$ at normalized minor radius r_{eff}/a_{99} of 0.55, 0.79, and 0.97 for the discharges with transit-time damping (left) and Landau damping (right). The sharp drop of $|df(v_\parallel)/dv_\parallel|$ at r_{eff}/a_{99} = 0.79 observed indicates the flattening of the ion velocity distribution near the resonance velocity of 200 - 300 km. The sharp increase of kinetic energy $E_\parallel$ associated with the onset of MHD wave appears at r_{eff}/a_{99} = 0.79, where the MHD wave is excited, while the gradual increase of $E_\parallel$ is observed in the plasma core.

The gradual increase of perpendicular kinetic energy $E_\perp$ at r_{eff}/a_{99} = 0.79 is due to the diffusion of kinetic energy in velocity space (thermalization). In contrast, the gradual increase of parallel kinetic energy $E_\parallel$ in the core is due to the diffusion of kinetic energy in real space (inward energy flux) as illustrated in Figure 3. In conclusion, the kinetic energy in the core increases after the onset of the MHD burst, especially in the discharge with Landau damping, while the MHD wave is excited near the plasma periphery. This experiment demonstrates that the wave-particle interaction, such as transit-time and Landau damping, occurring near the plasma edge contributes to the increase of core ion temperature, which is more favorable in the burning plasma.

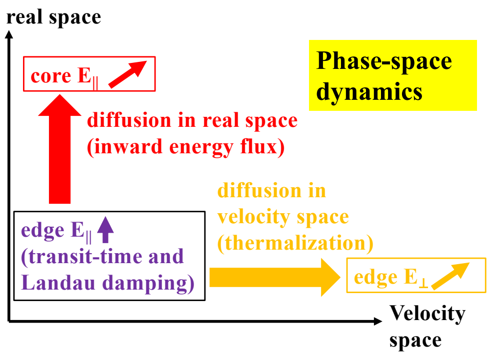

Fig.3. Diagram of phase-space dynamics observed in LHD plasma.

REFERENCES

[1] YOSHINUMA, M. et al., Fast Charge Exchange Spectroscopy for Measurements of Ion-Velocity-Space Distribution Function, Plasma Fusion Res. 19 (2024) 1402037.
[2] HE, Y.E. et al., T_i/Te effects on transport in EAST low q_{95} plasmas, Nucl. Fusion 64 (2024) 076064.
[3] SEO, J, et al., Ion heating by nonlinear Landau damping of high-n toroidal Alfv´en eigenmodes in ITER, Nucl. Fusion 61 (2021) 096022.
[4] IDA, K. et al., Direct observation of mass-dependent collisionless energy transfer via Landau and transit-time damping, Commun. Phys. 5 (2022) 228.
[5] KOBAYASHI, T. et. al., Detection of bifurcation in phase-space perturbative structures across transient wave–particle interaction in laboratory plasmas, Proc. Natl. Acad. Sci. 121 (2024) e2408112121.
[6] SKJÆRAASEN, O, et al., Local transit-time dissipation and Landau damping, Phys, Plasmas 6, (1999) 3435.