Observation of bipolar velocity-space signature of ion Landau damping

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Collisionless interaction between particle and wave causes the deformation of ion velocity space from Maxwell-Boltzmann distribution. And the energy transfer from wave to particle occurs in collisionless plasma by this process. We present the observation of the bipolar velocity-space signature of ion distribution function as the evidence of Landau damping based on direct measurement of velocity space on carbon ion using fast charge exchange spectroscopy with a time resolution (~ 10 kHz) less than ion-ion collision time in the plasma with the MHD burst. The resonant phase velocity evaluated from the bipolar velocity-space signature agrees with the phase velocity estimated from the frequency of the MHD burst measured with the plasma displacement and the perturbation of the magnetic field. The excellent agreement between the resonant phase velocity and the wave's phase velocity excited in the plasma is clear evidence for the Landau damping in LHD.

The LHD is equipped with five neutral beams (NBs), and three of them are injected in the direction parallel to the magnetic field, and two of them are injected perpendicular to the magnetic field. In this experiment, the beam species of three parallel NBs are hydrogen, and the beam species of two perpendicular NBs are deuterium, and neutrons are mainly created by the reaction between perpendicular beam and plasma. Therefore, the amount of energetic trapped ion injected by perpendicular deuterium NBs is monitored by the neutron flux measured with a scintillation detector [1]. The charge exchange spectroscopy [2] is used to measure ion velocity distribution along the line of sight. There are two lines of sight, one is parallel to the magnetic field, and the other is perpendicular to the magnetic field. The magnetic probes are installed inside the vacuum vessel at the toroidal angle of 18, 90, 126, 198, 270, and 342 degrees. The intensity of the electron cyclotron emission (ECE) [3] is proportional to the plasma electron temperature, T_e. ECE diagnostic is located at the toroidal angle of 198 degrees. Because the plasma electron temperature is constant on a magnetic field, the perturbation of the equi-temperature plasma surface is equivalent to the perturbation of the magnetic flux surface. Therefore, the perturbation of the magnetic field inside the plasma can be measured from the displacement of equi-temperature plasma surface as $-T_e/\nabla T_e$, where ∇T_e is the temperature fluctuation in the frequency range of 1-10 kHz and ∇T_e is the quasi-state (< 40 Hz) temperature gradient.

The Landau damping is observed in the plasma when the MHD burst with large amplitude occurs with deuterium beam injection perpendicular to the magnetic field. When the MHD bursts occur, the deuterium beam pressure decreases as indicated by the drop of neutron emission rate. Both ion and electron temperature increase after the MHD burst, which indicates the energy transfer from beam to bulk plasmas. The increase of temperature at $r_{eff}/a_{99} = 0.8$ is not due to the energy release from the core plasma. The RF intensity with 880MHz measured with an RF radiation probe [4] shows a sharp increase at the onset of the MHD burst. This signal is widely used as a timing indicator for the energetic ion loss from the plasma and is also is used as the reference timing for conditional averaging. This is because the RF radiation probe has a high time resolution and high sensitivity to the high-frequency RF signals excited by the loss of the energetic ions at the plasma edge [5]. In this experiment, the energy transfer from energetic deuterium to carbon impurity is observed through the MHD burst and the wave frequency shows down chirping due to the phase space re-distribution of energetic deuterium. The resonant phase velocity evaluated from the bipolar velocity-space signature agrees with the phase velocity estimated from the frequency of wave measured with the plasma displacement.

The excellent agreement between the resonant phase velocity and the wave's phase velocity excited in the plasma is clear evidence for the Landau damping. These results strongly impact nuclear fusion research because the energy transfer from energetic ion to bulk ion is an essential issue in nuclear fusion plasma. The energy transfer from the alpha particle (energetic Helium ion) to fuel ion (deuterium and tritium) through wave-particle interaction is one of the crucial issues in fusion plasma because most alpha particle energy is transferred to electrons through collisions. However, ion heating is indispensable to maintain the nuclear fusion reaction. This heating scenario using wave-particle interaction is called the α-channeling technique [6]. The energy transfer from energetic ion to impurity ion through wave-particle interaction observed in this experiment strongly supports the realization of the α-channeling technique.

References

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