§3. Studies of Energetic Particle Confinement

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In a magnetically confined nuclear fusion reactor, good particle confinement including fusion born alpha particles is strongly required for the sustainment of self-igniting plasma. The aim of our research is to clarify the physics and the improvement of both production and confinement of fast-ions toward the realization of Heliotron type nuclear fusion reactor. On LHD, we can consider the isotropic fast-ion confinement utilizing with many different kinds of heating system consisted of the perpendicular and tangential neutral beam injection (NBI) and ion cyclotron range of frequency (ICRF). Moreover, the existing diagnostics and newly developed ones including fast-ion charge exchange spectroscopy (FICXS) and corrective Thomson scattering (CTS) which can measure the spatial and velocity space profile of ions can give us the information of classical fast-ion transport and anomalous transport of fast-ions in detail. These researches have been done mainly at the plasma heating physics group and partly at the high-Ti group on LHD. Outline of major topics are described below.

1) Observation of GAM in NBI-heated plasmas

At low density LHD plasmas, up-chirping frequency n=0 mode was observed when the counter-NB was injected. The mode was categorized to two-groups according to the electron temperature (T_e) dependence of its initial mode frequency. Since the frequency of the one group has $T_e^{1/2}$ dependence, it was identified as Geodesic Acoustic Mode (GAM). The other group shows very weak dependence on T_e. It seems to depend on the orbital frequency of fast-ions produced by the NB. To understand this weak T_e dependence, we have expanded the GAM theory shown in [1] with fast-ion energy slowing-down spectra deformed by the charge exchange loss process and found a solution similar to the experimental observation [2]. Thus, the other mode was also identified as GAM.

During those GAM activities, it was observed that the energy spectra of fast-ions of around 150keV were deformed with the bursting GAM activities. This deformation of the fast-ion spectra can be explained by the clump-hole formation by theory [3].

It was also observed that the energy spectra of low energy ions were deformed with the bursting GAM activities. The deformation was significantly observed below 5keV. The effective ion temperature was evaluated from the slope of the energy spectra of low energy ions. The evaluated ion temperature increases with the increase of the time integration of the mode amplitude, which indicates the power of the mode, was transferred to the bulk ions.

2) Studies of interaction between fast-ions and Alfvén eigenmodes

The influence of toroidicity induced Alfvén eigenmode (TAE) on fast-ion transport in helical plasmas was intensively studied on LHD. The amount of fast-ion loss was compared with the amplitude of the TAE and their dependence on the amplitude was examined. Here, the amplitude was normalized by the operational magnetic field strength of LHD. It was found the loss amount can be linearly scaled with the normalized mode amplitude when the amplitude was small ($\delta b_\theta^{TAE}/B_t < 10^{-4}$). When the amplitude exceeds the value, the scaling was changed. It scaled with the square of the amplitude. This indicates the loss mechanism was changed from convective type loss to diffusive one. A simulation of fast-ion loss with the mode activity was performed by using DELTA5D. The result shows the transition of loss mechanism at a certain threshold level of the mode amplitude as is similar to the experimental observation. In the region where the loss is linearly scaled with the mode amplitude, the loss occurred for barely confined fast-ions around the loss boundary. While the region where the loss is scaled with the square of the amplitude, the fast-ions confined at the interior regions were lost diffusively. This simulation results confirm the implication of experimental results.

3) Observation of Fishbone-like events

On recent LHD high-ion temperature plasmas, a new fishbone-like mode was observed. The mode was observed when the plasmas were heated by perpendicular NBIs. Thus, the mode was considered to be excited by perpendicular fast-ions. The mode locates at $\iota/2\pi$=1 surface. The mode has a precursor of around 3kHz and propagates to electron diamagnetic direction. The structure of the precursor mode has typical resistive interchange mode (RIC) structure. The frequency of the fishbone-like mode is starting from ~7kHz and chirps down to 3kHz. There are many similarity were found between this fishbone-like mode and energetic particle driven wall mode [5] and/or Off-axis fishbone mode [6] which are observed in Tokamak devices. Further investigation is necessary to clarify the character of the mode.

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