§2. Indication of Bulk-ion Heating by Energetic Particle Driven Geodesic Acoustic Modes on LHD

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Zonal flows and the Geodesic Acoustic Mode (GAM) reduce the anomalous transport of bulk ions. The excitation of GAMs by energetic particles have been reported in several experiments such as JET, DIIID and LHD. Energetic particle driven GAMs are attractive since this mode theoretically might enhance ion heating efficiency of highly energetic particles and fusion born alpha-particles [1] through the channeling effect[2]. However this theory has not been validated in experiments yet.

On the Large Helical Device (LHD), ion temperature increase, which was evaluated from the low energy neutral spectra, was observed with excitation of the Energetic-particle driven Geodesic Acoustic Mode (EGAM) for the first time, as shown in Fig.1. This phenomenon was observed when the high energy Neutral Beam (NB) of ~170keV was injected into very low density plasmas below ~1x10^{18}m-3 sustained by Electron Cyclotron Heating (ECH). It was found that the enhanced ion heating by the mode activity was the most probable mechanism for this phenomena. This suggests the existence of a new energy channel of bulk-ion heating by energetic particles through the EGAM.

Several processes were assessed as causal mechanism to explain this phenomenon, i.e., (1)change of measured ion spectra due to the orbit topology change, (2)increase of

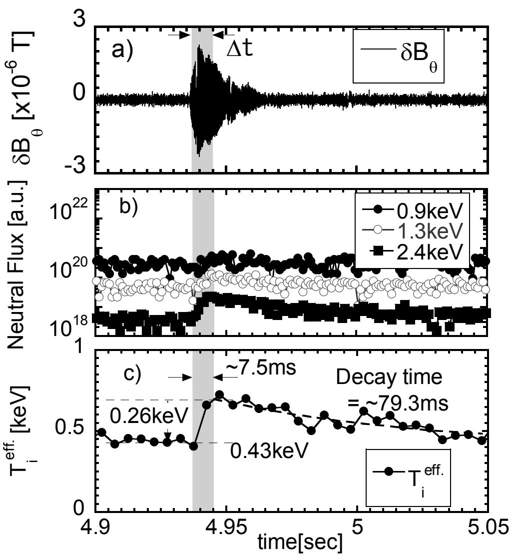

Fig.1 Typical waveforms of (a)magnetic-fluctuation (Mirnov-coil), (b) neutral flux and (c) effective ion temperature evaluated from the neutral particle spectra during an EGAM activity.

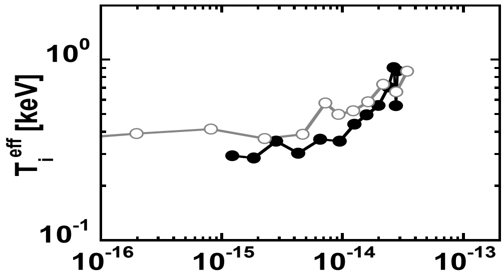

Fig.2 Variation of effective ion temperature with the increase of time integrated power of EGAM ($\int_{t_0}^{t_0+\Delta t}(\delta B_\theta)^2 dt$). Open and closed symbols indicate variation of these values for particular EGAM events. The time duration of T_i^{eff} rise was chosen as Δt (see Fig.1).

classical ion heating power by energetic particles, (3) enhancement of energy confinement properties and (4) enhanced ion heating by the EGAM. The first candidate is ruled out by comparing the reconstructed neutral energy spectra before and after the EGAM activities with several assumptions of proper ion temperature profiles. It was found the phenomena was due to ion temperature increase at the core rather than the temperature broadening, which is expected to be caused by radial excursion of bulk ions with the interaction of the mode activities. The second candidate is also ruled out although deformation of energetic particle spectra by the EGAM activity and the increase of energetic particle flux whose energy was close to the critical energy were observed in the series of experiments. It was found that the expected ion-heating power increase by the spectral deformation was much smaller than the sum of original ion-heating power from energetic ions and that from bulk-electrons. The third (3) and the fourth (4) candidates were examined by simple power balance analysis, where the ion heating power of ~0.8[kW/m^3] and energy confinement time of ~360[ms] were assumed during the quiescent phase. The former value is evaluated by TASK-3D code. The later, which has factor of four difference from the decay time of effective ion temperature after the mode activity as shown in Fig.1(c), was evaluated from the power balance using the heating power. From the analysis, it turned out that the observed ion temperature increase was difficult to reproduce even if an infinitely large confinement time was assumed. On the hand the observed ion temperature increase was reproduced by assuming the increase of ion heating power from ~0.8[kW/m^3] to ~4[kW/m^3], which is same order of expected EGAM ion-heating power as evaluated from the potential fluctuation measured by HIBP and by using the formula shown in [1]. In addition to these analyses, increase of effective ion temperatures was correlated with the time integrated power of the mode (Fig.2). This also suggests ion heating from the mode activities.

1) M. Sasaki, et al.: Plasma Phys. and Control. Fusion 53 (2011) 085017.
2) Fisch, N. J. and Herrmann, M. C.: Nucl. Fusion 34 (1994) 1541