Effect of energetic-ion-driven MHD instabilities on energetic-ion-transport in Compact Helical System and Large Helical Device

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1. Introduction

Energetic-ion-driven MHD instabilities such as energetic-particle continuum modes (EPM) [1] and toroidicity-induced Alfvén eigenmodes (TAE) [2] are of great concern in current fusion experiments because those instabilities may lead to anomalous transport of energetic ions/alphas in a future D-T burning plasma. Alfvénic modes associated with energetic ions are regularly observed in tokamaks plasmas with strong, super Alfvénic ion tails [3-5]. They are also destabilized in heliotron/stellarator plasmas [6,7]. In heliotron/stellarator experiments, the confinement property of magnetically trapped ions has been so far one of key arguments. Because of continuous efforts in optimizing magnetic field configuration, the issue related to trapped-ion orbit is currently being solved. Actually, ion cyclotron resonance heating (ICRH) experiments in the Large Helical Device (LHD) showed that helically trapped energetic ions produced by ICRH were well confined in a inward shifted plasma, so-called drift-optimized configuration [8]. However, a great deal of attention should be paid to redistribution and/or losses of energetic ions induced by energetic-ion-driven MHD instabilities because the interplay between energetic ions and energetic-ion driven instabilities is not completely understood yet. Therefore, phenomena observed in existing experiments should be carefully studied toward the realization of fusion reactor based on heliotron/stellarator concept. In this work, experiments on MHD instabilities excited by neutral beam (NB)-injected energetic ions and consequent energetic-ion transport and/or loss have been conducted in two helical devices, i.e. small-scale device Compact Helical System (CHS) and large-scale machine LHD. This paper describes representative results on beam-ion losses due to EPMs and TAEs in CHS and recent results on beam-ion behavior while EPMs are present in LHD.

2. Experimental setup

2.1 Beam ions on LHD and CHS

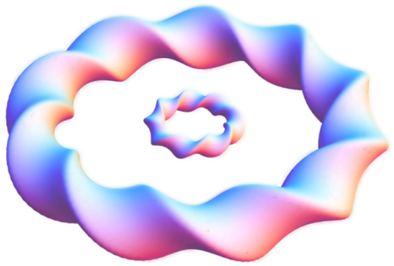

Figure 1. Plasmas shapes of LHD and CHS.

Last closed flux surfaces (LCFSs) for CHS and LHD are shown in Figure 1. The CHS was an l=2 small-scale helical device with a toroidal period number M of 8. Its major and minor radii were R of 1 m and a_p of 0.2 m, respectively. The CHS was shut down in 2006. The LHD is a large-scale helical device with l/M=2/10, having R of 3.9 m and a_p of 0.6 m. Although the LHD has a natural divertor intrinsically whereas the CHS did not, these two are similar in the magnetic field structure but the LHD configuration is more drift-optimized. Rotational profiles for both equilibria are characterized by negative magnetic shear over an entire region of plasma.

Energetic ions essential in driving energetic-ion driven MHD instabilities are generated in plasmas by injecting NBs. The CHS was equipped with two positive-ion source based NB injectors (P-NBIs). One injected hydrogen beams of which injection energy E_b and the port-through power P_{nb} are ~ 40 keV and ~ 0.8 MW, respectively. The other provided beam ions with E_b/P_{nb} of 32 keV/0.8 MW. Both injectors were oriented in the same direction. Normally, beam ions were tangentially co-injected in CHS. The LHD is equipped with three negative-ion source based NB injectors (E_b/P_{nb}=180 keV/~5 MW for each) and one perpendicular P-NBI (E_b/P_{nb}=40 keV/~6 MW). Two of the N-NBIs are oriented in the same direction and the rest is oriented to be opposite. The ratio of parallel velocity of tangential beam ions $v_{b//}$ to Alfvén velocity v_A ranges ~0.2<$v_{b//}/v_A$<~0.8 for CHS and ~0.2<$v_{b//}/v_A$<~2.5 for LHD [9]. Experiments were performed in relatively low n_e plasmas to increase beam ion's pressure through the long slowing down time τ_s environment. Also, most discharges were done in the low-B_t condition (B_t<1 T) to decrease v_A.

2.2 Fast-particle diagnostics

Both devices are equipped with a comprehensive set of fast-particle diagnostics consisting of charge-exchange neutral-particle analyzers (NPAs) for confined beam ions, scintillator-based lost-fast ion probes (SLIPs) at the outboard and inboard sides and a directional Langmuir probe for escaping beam ions. These play an important role in studying anomalous transport due to EPMs/TAEs as well as neoclassical confinement of energetic ions. In LHD, the SLIP placed at the outboard side is new and started to work in the 2008 campaign. Fast-particle diagnostics on CHS are available in Ref. 10. As for LHD, diagnostics on fast particles are well summarized in Ref. 11.

3. Experimental results

3.1 Beam-ion losses due to EPMs and TAEs in CHS

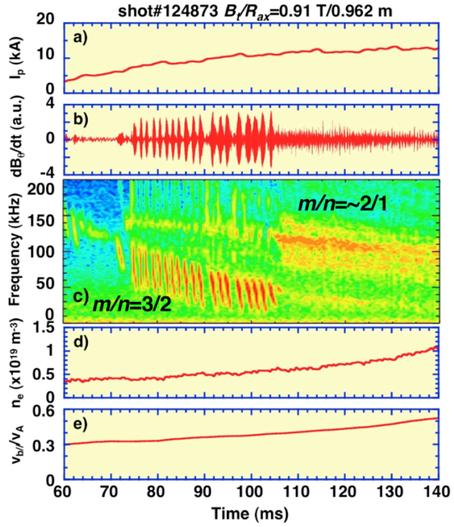

Figure 2. Typical CHS discharge with EPMs and TAEs. a) Ohkawa current, b) dB_θ/dt, c) spectrogram on Mirnov coil signal, d) n_e and e) $v_{b//}/v_A$.

EPMs and TAEs destabilized by co-going beam ions were often observed in relatively low-density plasmas ($n_e \approx (0.5\sim2) \times 10^{19}$ m^{-3}) [12]. Fast-particle diagnostics mentioned above revealed that beam ions are anomalously transported toward the outboard side of the torus due to those bursting MHD modes. EPMs were preferably excited in an early phase of NB-heated discharge where beam-ion pressure was relatively high due to longer τ_s through low n_e and high T_e, and beam-driven net current was still developing. A representative discharge on beam-ion driven instabilities is shown in Figure 3. In the initial half of the discharge (t<105 ms), repetitive bursting fluctuations (m/n=3/2) are seen, rotating in parallel to the velocity of beam ions. Because the observed mode frequency was much lower than the TAE gap frequency and each burst was accompanied by rapid frequency downshift, this instability was recognized to be EPMs. As $v_{b//}/v_A$ increases, EPMs (f<100 kHz) disappear and weaker fluctuations (m/n=~2/1) having higher frequency (f>100 kHz) became intense. This higher frequency modes propagates poloidally in the ion-diamagnetic direction and toroidally in the co-direction, and were strongly destabilized when the condition of $v_{b//}/v_A$>1/3 was fulfilled. This mode is recognized to be TAE because the observed frequency is in the TAE gap and the dependence of the mode frequency on density matches that for TAE.

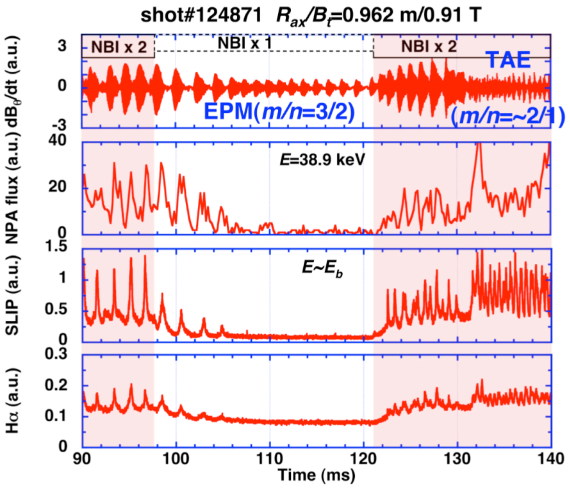

Figure 3. Time traces of dB_θ/dt, fast-netral flux, beam-ion loss rate to SLIP and Hα emissivity.

Figure 3 shows time evolutions of Mirov coil signal, fast-neutral flux, beam-ion loss rate to SLIP placed at the outboard and Hα light emissivity measured at the edge region of the outboard side. Correlated with recurrent EPM bursts, fast-neutral flux, beam-ion loss rate to SLIP and Hα light intensity are strongly enhanced. After one of the two tangential NBs was turned off, the amplitude of EPM became smaller. Concurrently, fast-neutral flux and beam-ion loss rate to SLIP decreased as time went by. Although bursting EPMs were still present in the single NB heating phase, beam-ion losses associated with EPM bursts were not seen. Intense beam-ion losses appeared again after 2nd NB turn-on. These clearly indicate that beam-ion losses depend on the amplitude of EPM bursts, i.e., beam-ion loss rate increases as the EPM amplitude increases. After t=130 ms, dominant instabilities became TAEs. Beam ions were expelled also in the TAE phase although its fluctuation was smaller than EPM.

To look into the effect of perturbed field on beam ion's orbit in CHS, the guiding center orbit simulation considering possible level of magnetic fluctuation (δB~10^5-10^4 T) was performed by use of DELTA5D code [13]. The perturbation is represented through $\delta \mathbf{B}=\nabla\times\alpha\mathbf{B}$, where α is a general function of position and amplitude. As shown in Figure 4, the calculation suggests that orbit of co-going beam ion in R_{ax}/B_t of 0.962 m/0.91 T tends to be expanded toward the outboard side of the torus due to the presence of magnetic fluctuation and consequently goes across the LCFS. This result qualitatively supports experimental observation.

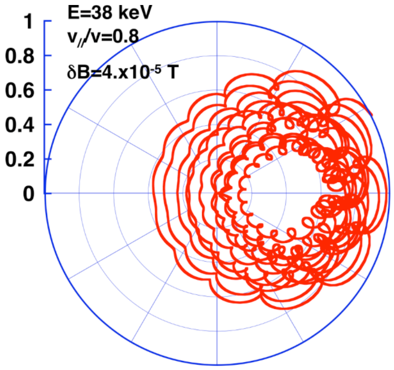

Figure 4. Orbit of co-going beam ions (H+, 40 keV) affected by the magnetic perturbation.

3.2 Beam-ion losses due to EPMs in LHD

In LHD, non-classical transport of co-going beam ions due to bursting TAEs has been so far recognized from the measurement of charge-exchanged fast neutrals [14]. To increase understanding of beam-ion behavior while beam-ion driven instabilities occur in LHD, the SLIP was lately installed at the outboard side of horizontally elongated poloidal cross section [15]. The position of detector end on LHD is almost the same as that on CHS.

EPMs are often destabilized in LHD when NBs are tangentially injected into relatively low n_e plasmas (n_e~1x10^{19} m^{-3}). It looks that they are preferably excited when NBs are injected in the balanced manner. Figure 5 shows a typical EPM (n=2) shot in R_{ax}/B_t of 3.75 m/0.75 T (CCW). Similarly to EPM observed in CHS, the mode is characterized by a rapid frequency downshift, propagating in the co-direction. This implies that co-going beam ions are responsible for the excitation of EPMs. EPMs are not seen in a higher density plasma, for instance, n_e~2x10^{19} m^{-3} in R_{ax}/B_t of 3.75 m/0.75 T. Figure 6 shows time traces of the amplitude of magnetic fluctuation filtered in frequency of 10~40 kHz, fast-neutral flux measured with E//B-NPA oriented so as to detect fast-neutral particles charge-exchanged with co-going beam ions, beam-ion loss rate to SLIP at the outboard side and stored energy evaluated from a diamagnetic loop signal.

Similarly to CHS, correlated with each EPM burst, fast-neutral flux (E=148 keV) and beam-ion loss rate to SLIP significantly increase. Energy of detected beam ions is ~150 keV and is consistent with energy of anomalously transported beam ions measured with E//B-NPA. The E//B-NPA shows gentle change for lower-energy particle flux, ex. E=77.2 keV, correlated with each EPM bursts. It should be noted that the decay rate of lower-energy particle flux is much longer than that of particle of E=148 keV. This suggests that there exist co-going beam ions that are redistributed and continue slowing down in the plasma. Unlike LHD, the sign of beam ion's slowing down on NPA signal was not clearly seen in CHS. For CHS, it looks as if once co-going beam-ions are transported toward the outboard side, they are lost within a relatively shot-time scale.

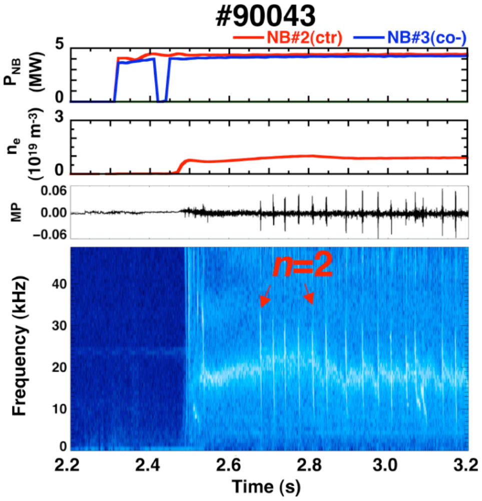

Figure 5. Typical EPM shot in LHD

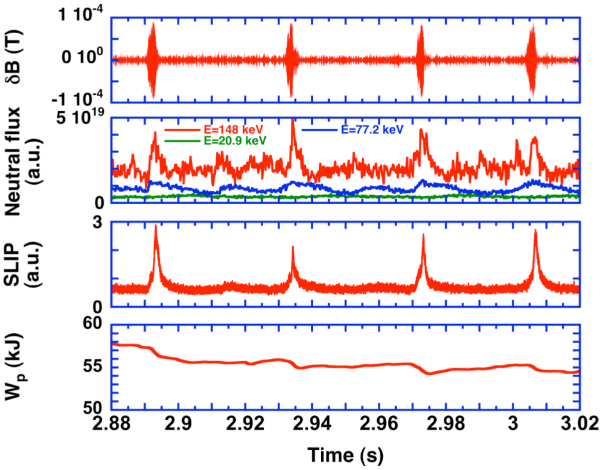

Figure 6. Time traces δB, fast neutrals, beam-ion loss rate to SLIP (E~150 keV) and W_p

TAE-induced beam-ion losses are also detected by means of SLIP in low-B_t, high-β discharges [16]. It is interesting to note that in addition to TAEs, the beam-ion loss rate to SLIP is enhanced by the resistive interchange modes (RICs) thought to be localized at the plasma edge. This is because TAEs are preferably excited in plasmas with higher bulk plasma β compared with the plasma where EPMs are often excited. Actually, the effect of RICs is superposed on the signal caused by TAEs. It looks as if there are synergic effects of TAEs and RICs on beam-ion transport and/or loss. Detailed analysis on TAE/RIC-induced losses is now ongoing.

4. Summary

Representative results on excitation of EPMs and TAEs and consequent beam-ion loss in CHS and recent observation on beam-ion losses due to EPMs/TAEs in LHD are described. The both devices are equipped with a comprehensive set of fast-particle diagnostics to study anomalous transport and/or loss of energetic ions as well as neoclassical confinement of energetic ions. Bursting EPMs are destabilized by co-injected beam ions in the high-beam ion pressure environment and give a significant effect on co-going beam ion in both experiments. In CHS, co-transit beam ions were transported toward the outboard side due to EPMs and were lost. The particle simulation considering perturbed magnetic field qualitatively supports the experimental observation. Beam ions were expelled also in the TAE (m/n=~1/1) phase although its fluctuation was smaller than EPM. The anomalous loss rate of beam ions increases as the amplitude of magnetic fluctuation increases. As for LHD, co-going beam ions escaping toward the outboard side are also detected in EPM discharges. Measurement of fast neutrals suggests that unlike CHS, there exist co-going beam ions that are redistributed due to EPMs and continue slowing down in the LHD plasma.

Acknowledgements

This work is partly supported by Grant-in-Aid for Scientific Research (B) of JSPS, No. 21340175 and No. 21360457.

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