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Fast Ion-Driven MHD Instabilities and Consequent Fast Ion Losses in the Compact Helical System

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Abstract. Impacts of fast-ion-driven MHD modes on fast ion transport have been investigated in a medium size helical device CHS having negative magnetic shear over an entire region of plasma. Recently, it was observed that bursting toroidicity-induced Alfvén eigenmodes (TAEs) excited by co-circulating beam ions enhance beam ion loss at the low magnetic field strength of 0.9 T. The flux of escaping beam ions steeply increases as the magnetic fluctuation level increases. Excitation of energetic particle modes (EPMs) due to co-circulating beam ions has been also observed in CHS ; the frequency range of these modes is located appreciably below the TAE gap frequency. Bursts of EPMs and TAEs recur periodically, correlated with increased beam ion loss. Fast particle diagnostics indicate that beam ions transported by these modes are rapidly lost to the large major radius side of CHS plasma in the horizontally elongated section. Particle simulation suggests that a perturbed magnetic field whose amplitude is consistent with the CHS experiment can rapidly increase the fast ion loss.

1. Introduction

Interaction between energetic ions and kinetically driven magnetohydrodynamics (MHD) modes is one of the key physics issues in current fusion experiments. In particular, the energetic particle modes (EPMs) [1] and Aflvén eigenmodes (AEs) [2] may lead to redistribution and/or anomalous loss of energetic alpha particles produced by the deuterium-tritium (d-t) reaction in a future burning plasma [3]. Anomalous loss of alpha particles should be avoided because this will result in loss of a self-ignited state. In addition, the localized heat load on the first wall due to impact of escaping alphas may seriously damage the device. Accordingly, excitation of these modes, which is sensitively dependent on fast ion distribution in real and velocity spaces and rotational transform profile $\iota/2\pi$, and effects of Alfvénic modes on fast ion confinement have been intensively studied in many tokamaks such as JET, TFTR and JT-60U [4-8]. The MHD instabilities mentioned above have been also observed in helical/stellarator devices, e.g. CHS, LHD and W7-AS, which offer an alternative concept for a magnetic confinement fusion reactor [9-12]. In this paper, we report recent results on fast-ion-driven MHD instabilities and their influences on fast ion transport in the Compact Helical System (CHS) using several fast ion diagnostics with improved performance ; such fast ion losses due to EPMs was briefly reported in Ref. 11. Subsequently, detailed studies of escaping fast ions were performed by means of fast ion diagnostics with high time resolution [13]. Here, we mainly focus on the following three topics, i.e. 1) TAE-induced fast ion losses, 2) details on fast ion transport in an interior region of CHS plasma during EPMs and 3) particle simulation of fast ion loss by EPMs.

2. CHS experimental setup

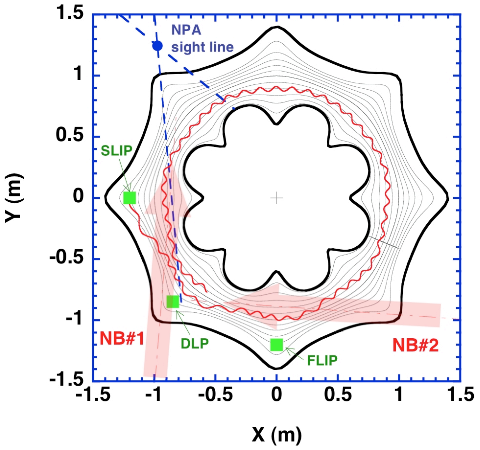

FIG. 1. Arrangement of NB injectors and fast particle diagnostics on CHS. The red solid line shows an example of orbit of fast ion (38 keV) reaching the SLIP in B_t/Rax of 0.9 T/0.974 m.

The CHS is a medium-sized helical device having a major radius of ~1 m and averaged plasma minor radius of ~0.2 m and is characterized by its low aspect ratio of 5. Because of the low aspect ratio and non-axisymmetric magnetic field, an issue on fast ion orbit is one of key physics subjects. The magnetic configuration of CHS has negative magnetic shear over an entire region of plasma, introducing shear Alfvén continua that are different from those in tokamaks. In our experiment, fast ions, which play a key role in driving MHD instabilities, are generated in a plasma by injecting fast-neutral beams (NBs) as a substitute for alpha particles. The arrangement of NB injectors and fast particle diagnostics important for this work are shown in Figure 1. The CHS is equipped with two NB injectors (NB#1 of 40 kV/0.8 MW, NB#2 of 32 kV/0.8 MW). The fast ion experiment in CHS is characterized by the combination of a variety of fast particle diagnostics, i.e. scintillator-based lost fast ion probes (SLIP) [14], Faraday film-based lost fast ion probe (FLIP) [15], a directional Langmuir probe (DLP) [16] and a charge exchange (CX) neutral particle analyzer (NPA) whose viewing angle is horizontally variable. The SLIP and FLIP are capable of measuring energy and pitch-angle of escaping fast ions simultaneously. An array of detectors measuring Hα light emissivity is also used to obtain valuable information on fast ion behavior. As for the magnetic fluctuation measurement, toroidal and poloidal sets of the Mirnov coil arrays placed outside of plasma are employed in this study. Fast ion experiments in CHS were mainly performed in the magnetic configuration of R_{ax} = 0.962 m using hydrogen plasmas with the following parameters : the toroidal magnetic field strength B_t = 0.9~1.4 T, electron density n_e = (0.5~2)x10^{19} m^{-3}, injection energy of H^0 beam E_b = 30~39 keV and $v_{b//}/v_A \leq 0.5$, which is the ratio of the beam ions' velocity to the Alfvén velocity.

3. Experimental results

3.1 EPMs and Alfvén eigenmodes observed in CHS

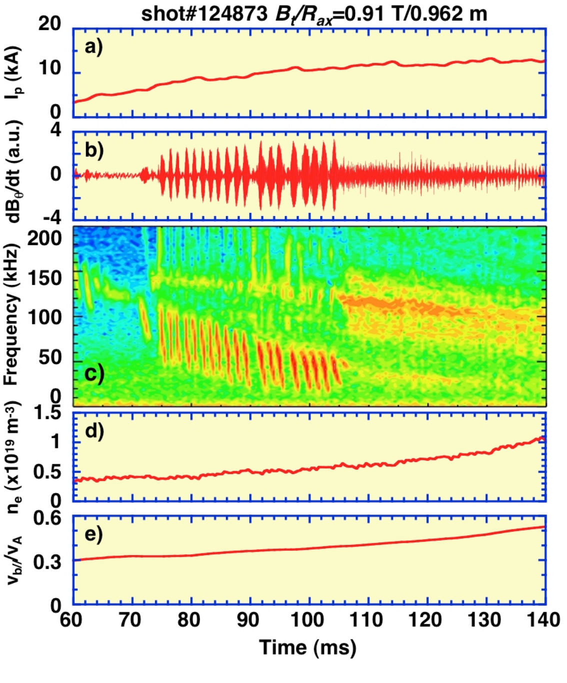

FIG. 2. Fast-ion-driven MHD instabilities observed in outward shifted configuration (R_{ax}=0.962 m) of CHS at low B_t (0.91 T). (a) net plasma current, (b) dB_θ/dt, (c) magnetic spectrogram, (d) line-averaged n_e and (e) $v_{b//}/v_A$.

Figure 2 shows typical time traces of the discharge where fast-ion-driven modes are destabilized in B_t/R_{ax} of 0.91 T/0.962 m, (a) co-flowing net plasma current dominated by Ohkawa current, (b) dB_θ/dt, (c) magnetic spectrogram, (d) line-averaged n_e and (e) $v_{b//}/v_A$ when two NBs with total port-through NB power P_{nb} of 1.6 MW are tangentially co-injected. In the initial half of the discharge (t < 105 ms), repetitive bursting magnetic fluctuations are seen. This mode is diagnosed to be n=2/m=3, where n and m stand for the toroidal and poloidal mode numbers, rotating in the ion-diamagnetic direction. It is characterized by a rapid frequency downshift from ~100 kHz to ~ 40 kHz with a time scale of ~ 1 ms. This instability is not seen in the high n_e regime, i.e., low beam β regime. As n_e, in other words, $v_{b//}/v_A$ increases, the bursting modes having f < 100 kHz disappear and weaker fluctuations having higher frequency (f > 100 kHz) become more intense. The higher frequency modes are strongly destabilized when the condition of $v_{b//}/v_A$ >

1/3 is fulfilled. Here v_A is evaluated from line-averaged n_e and the effective ion charge Z_{eff} is assumed to be 3. The mode numbers are measured as n=1/m~2. This mode also propagates in the ion-diamagnetic direction. As for this discharge, the rotational transform and shear Alfvén continua for the n=1 and n=2 modes are shown in Figure 3. The frequency of repetitive bursting modes accompanied with the rapid frequency downshift in the time range of t < 105 ms is located within the Alfvén continua, where a strong damping effect is expected. In addition, the m number is specifically identified without mixing for this instability. Therefore, we may reasonably conclude that observed bursting modes are the so-called EPMs. With regard to higher frequency MHD instabilities (f > 100 kHz) that appear for t > 105 ms, they are thought to be core-localized TAEs [11] for the following reasons. The shear Alfvén spectrum calculated with the experimental parameter range suggests that the observed mode with f > 100 kHz is n=1 TAE. Also, the condition of the sideband excitation, i.e. $v_{b//}/v_A$ > 1/3 is satisfied in this case. In the CHS configuration, the rotational transform increases towards the plasma edge. Because of this, the TAE gap does not expand to the edge region, suggesting that the mode is core-localized in CHS.

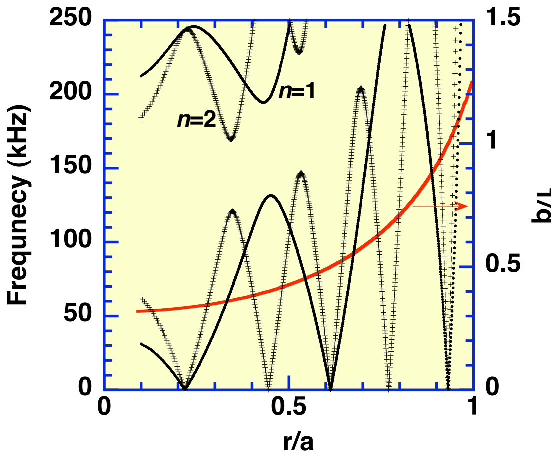

FIG. 3. Shear Aflvén continua (2D) for n=1 and 2 modes and rotational transform (1/q) where q is the safety factor for R_{ax} = 0.962 m. Only poloidal mode coupling is taken into account and $n_e(0)$ is $1.0x10^{19}$ m^{-3} in this calculation. Z_{eff} is assumed to be 3.

3.2 TAE-induced fast ion transport

The impact of TAE instabilities on fast ion transport is of great concern. In the previous experiment with one NB injector, significant transport and/or loss of fast ions by TAEs were not observed. This is probably due to the low amplitude of excited fluctuation ($\delta B_\theta < 10^{-5}$ T at the Mirnov coil position) [10]. The recent experiments reveal that repetitive anomalous losses of fast ions are significantly induced due to n=1 TAEs ; the gap for these modes is formed by a coupling of m=2 and 3 poloidal modes and results in δB_θ over 10^{-5} T when two NBs are tangentially co-injected. Figure 4 shows enlarged waveforms of the TAE shot shown in Figure 2, together with the poloidal cross section of CHS where measurements are carried out. Correlated with the TAE bursts of δB_θ ~ $2x10^{-5}$ T at the Mirnov coil position, lost fast ion probes placed at the large major radius side of the horizontally elongated cross section show

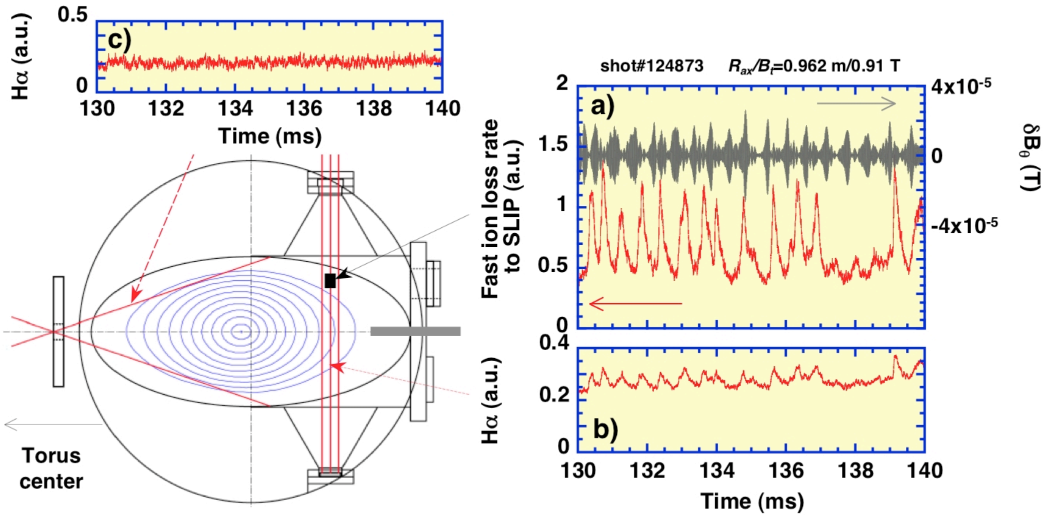

FIG. 4. Waveforms of TAE shot in R_{ax}/B_t of 0.962 m/0.91 T, which is the same as that shown in Figure 2. (a) amplitude of magnetic fluctuation in Tesla measured with the Mirnov coil placed outside the plasma. The signal is filtered in the range from 95 kHz to 120 kHz. (b) Hα light emissivity in r/a > 0.9 at the outboard side. (c) Hα light emissivity in r/a > 0.9 at the inboard side.

periodic increase in the flux of lost fast ions with energy close to E_b, indicating that the beam ions are expelled due to the TAE bursts. From the pitch-angle of lost fast ions measured with the SLIP and the subsequent orbit calculation, we identify that lost fast ions have co-going transit orbits that deviate substantially from magnetic flux surfaces on the outboard side. The time trace of the Hα light emissivity at the same diagnostic port but different toroidal angle behaves like the fast ion probes' signal. The periodic increases of Hα light emissivity at the outboard side (Fig. 4b) are thought to be due to the impact of fast ions transported to the peripheral domain, where dense neutral hydrogen gas is present. Meanwhile, no remarkable change in Hα emissivity at the edge region of the inboard side is seen (Fig. 4c). These observations tell us that co-going transit beam ions are transported to the outboard side resulting from the TAE bursts and are lost. CX fast neutrals have been also measured with the NPA in this experiment. However, because of the poor time resolution (0.2 ms) of the system, periodic changes of the fast neutral flux associated with the above-shown TAE bursts were too rapid to be resolved. Fluxes of lost fast ions when the TAE activities are destabilized are dependent on δB_θ. Figure 5 shows fast ion loss rate to the probe as a function of δB_θ. It is seen that fast ion loss flux increases as δB_θ increases.

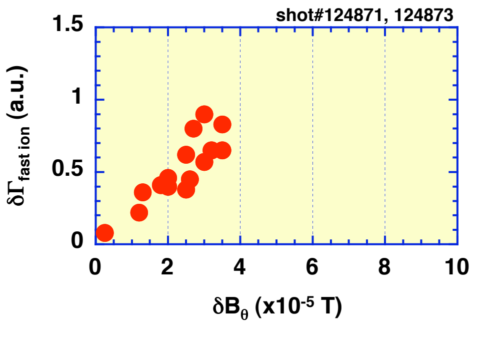

FIG. 5. Fast ion loss flux $\delta\Gamma_{fast\ ion}$ evaluated from the SLIP as a function of amplitude of δB_θ measured with the magnetic probe placed outside the plasma for the TAE shots.

3.3. Impact of EPM on fast ion transport

Figure 6 shows the time traces of (a) dB_θ/dt, (b) fluxes of CX fast neutral particles having the energy of 39.1 keV, (c) Hα light emissivity, and (d) SLIP signal originating from lost fast ions having energy close to E_b while EPM bursts with the mode number of n=2/m=3 are excited by co-circulating beam ions in a low density plasma (n_e~0.6x10^{19} m^{-3}). The mode frequency of each burst chirps downward from ~100 kHz to ~50 kHz within a short time scale less than 1 ms. The value of δB_θ ranges from 6.0x10^{-5} T to 8.0x10^{-5} T in this case. Correlated with the EPM bursts, pulsed increases are observed in NPA, SLIP and Hα signals. It is noted that signals of the FLIP and DLP show similar behavior to that of the SLIP. It is seen that the evolution of NPA flux is earlier than that of the SLIP. The increase of NPA flux is caused by transport of fast ions to the peripheral domain where the neutral hydrogen is much denser than that in the core. The NPA flux begins to increase right after the magnetic fluctuation begins to evolve whereas the evolution of lost fast ion flux is somewhat delayed. This is because the NPA signal responds to the presence of fast ions in the interior region of a plasma. It should be noted that the NPA oriented to the tangential direction shows that correlated with the EPMs, only the fast particle flux only in the energy range close to E_b (~40 keV) increases periodically whereas the fluxes of partially thermalized particles do not. This suggests that fast ions transported to the edge region are not well confined [13]. These experimental observations indicate that the EPMs cause significant effects on fast ion transport, leading to rapid loss of fast ions. It is also indicated that the EPMs are stabilized after an expulsion of fast ions.

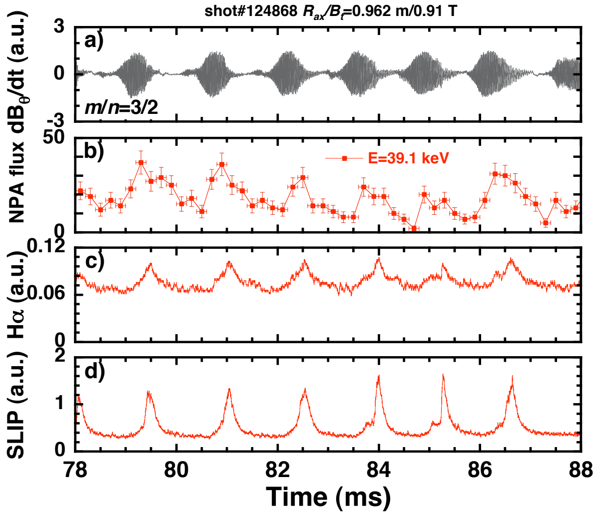

FIG. 6. Time evolution of (a) dB_θ/dt, (b) fast neutral flux measured with NPA set to be tangential, (c) Hα light emissivity measured at the outboard side of the torus and (d) lost fast ion flux measured with the SLIP.

It is interesting and important to study fast ion behaviors in an interior region of plasma when EPMs are excited in order to better understand the interplay between the mode and fast ions. Lately, we have found that the DLP can work as a fast ion probe [16]. The DLP in CHS has multi-probe tips and is designed to be tough enough to withstand the heat load of an NBheated plasma and provides local information of fast ion behavior inside plasma although information of fast ions such as energy and pitch-angle is not provided. Figure 7 shows fast ion behavior at different positions in the vicinity of plasma boundary while EPMs are excited in B_t/R_{ax} of 0.91 T/0.962 m. The interesting observation is that correlated with the magnetic fluctuations, fast ion fluxes reaching the DLP are strongly oscillatory. Such a strong oscillation does not appear on signals of SLIP and FLIP placed at the outside of plasma. This is supposed to be due to results from interaction between the rotating modes and fast ions. The time-resolved fast ions transport to the peripheral region due to the EPM has been clearly seen. Velocity of radial movement of fast ions is fairly high and is evaluated to be about 6x10^2 m/s. The internal measurement of the fast ions also suggests that they are rapidly transported by the EPMs out of the central CHS plasmas at B_t of 0.91 T.

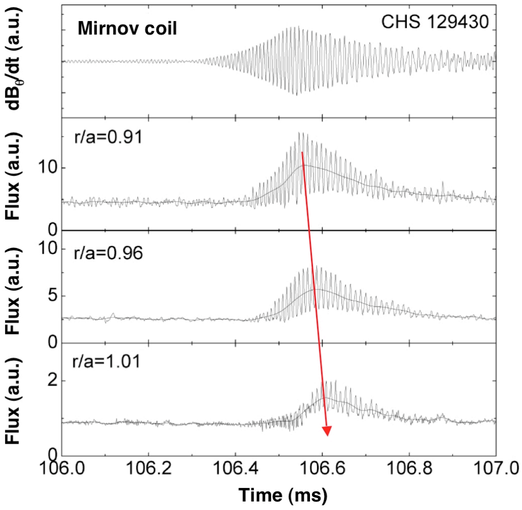

FIG. 7. Time variation of fast ion flux reaching the DLP for three different locations, i.e, r/a =0.91, 0.96 and 1.01 due to the EPM in B_t/R_{ax} of 0.91 T/0.962 m. The red arrow line represents the trace of peak position of fast ion flux.

4. Particle simulation of fast ion loss by EPMs

Motivated by heavy ion beam probe data, we have assumed an (n=2/m=3) EPM internal mode structure in order to simulate the fast particle loss induced by EPMs using the DELTA5D code. The results indicate that a perturbed field whose amplitude is consistent with the CHS experiment can rapidly increase the fast ion losses as compared to losses in the stationary magnetic field (Fig. 8). It has also been shown that fast ion losses are strongly enhanced as the mode amplitude increases, as seen experimentally. Moreover, the frequency downshift of EPM fluctuation can strongly influence the fast ion confinement compared with a fixed mode frequency.

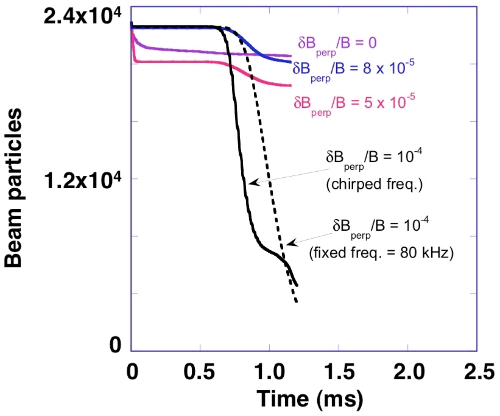

FIG. 8. Time evolution of number of confined beam ions for the different amplitude of magnetic fluctuation in the CHS configuration.

5. Summary

Recent results on fast-ion-driven MHD instabilities and consequent fast ion transport in the low aspect ratio helical system CHS are presented. It was shown that the n=1 TAE instabilities driven by co-circulating beam ions lead to significant beam ion losses toward the outboard side of the torus. Fast ion losses are enhanced as the fluctuation amplitude of the TAEs or EPMs increases. Detailed studies of the fast ion transport due to the EPMs (n/m=2/3) characterized by periodic recurrence and rapid frequency downshift have revealed that the effect of EPMs on fast ion confinement is significant and fast ions affected by the EPMs can be rapidly lost when EPMs are present.

Acknowledgements

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