Fast-ion transport during repetitive burst phenomena of Toroidal Alfvén Eigenmodes in the Large Helical Device

M. Nishiura 1), M. Isobe 1), S. Yamamoto 2), T. Tokuzawa 1), T. Mutoh 1), H. Funaba 1), K. Saito 1), T. Seki 1), S. Murakami 2), M. Osakabe 1), F. Watanabe 3), K. Toi 1), T. Ido 1), T. Nagasaka 1), K. Fujioka 4), Y. Fujimoto 4), M. Nakatsuka 4), T. Hirouchi 5), M. Sasao 5), LHD experimental group 1)

1) National Institute for Fusion Science, Toki, Japan
2) Kyoto University, Kyoto, Japan
3) Nagoya University, Nagoya, Japan
4) Osaka University, Suita, Japan
5) Tohoku University, Sendai, Japan

e-mail contact of main author: nishiura@nifs.ac.jp

Abstract. Alfvén instabilities induced fast-ion losses have been directly observed for the first time by a newly developed scintillator lost ion probe (SLIP) in the Large Helical Device (LHD). The SLIP can measure the pitch angle and gyro radius of escaped fast ions toward loss region. Neutral beam driven Alfvén Eigenmodes (AEs) are excited under the reactor relevant conditions: the ratio of fast ion (beam) speed υ_b and Alfvén speed υ_A is more than 0.3 ~ 4.0. The beta value for fast ions is considered roughly to be ~ 10%. Non-linear phenomena related to Alfvén instabilities are observed under such conditions. During repetitive Toroidal Alfvén Eigenmode (TAE) bursts, synchronized fast ion losses are observed by SLIP. From the orbit calculation the measured fast ion with pitch angle of 130 degrees and beam energy of 150 keV surely pass through the locations of TAE gaps. The orbit analysis found that the observed fast ions interact strongly with the excited TAEs. This result becomes the first experimental evidence of radial transport of fast ions predicted theoretically during TAE activities. In addition, from the correlation between stored energy degradation and fast-ion loss rate, it is found that fast-ion losses induced by TAE activities with low toroidal mode numbers categorize two phenomena without and with fast- ion loss enhancements, which indicate the fast-ion redistribution and loss.

1. Introduction

The fusion born alphas and the fast ions of neutral beam origin excite and drive the Alfvén instabilities in burning plasmas. In other situations, the fast ion populations are effectively enhanced by ion cyclotron resonant heating, and it also becomes the source of various instabilities. These instabilities induced fast ion losses are considered to lead to the degradations of plasma performance and the damages of first wall in a fusion reactor. It is essential to understand the instabilities driven by alpha particles and the resultant behaviors of alpha particles induced by MHD instabilities such as TAEs and energetic particle continuum mode (EPM) under reactor relevant conditions. To control the burning plasma, the theoretical predictions and the experimental corroborations become good approaches.

Many researchers have studied TAEs and related Alfvén instabilities in fusion plasmas, since the neutral beam driven TAEs are observed experimentally [1]. In view of the direct fast ion loss detection, the scintillator lost ion probe is considered to be one of the most useful tools for the researches on fast ion losses. In ASDEX-UG, the fast ion losses are observed directly by using the scintillator probe during high frequency MHD activities. They showed the good correlation between fluctuation frequencies of detected fast ion loss and MHD activities such as Alfvén instabilities [2]. The excited TAEs were observed for the first time in the compact helical system (CHS) with $l = 2 / m = 8$ heliotron configuration [3]. Here l

and m are the poloidal and the toroidal mode numbers of the helical plasma. The fast ion transports related to both EPM and TAE instabilities have been under intense studies in CHS [4]. In LHD, the sudden drop of stored energy during TAE activities has already reported in Refs.[5-8]. These experiments become the complements of tokamak reversed shear configuration and reactor relevant condition $\upsilon_{b//} > \upsilon_A$ during Alfvén activities. The neutral particle flux is measured by the neutral particle analyzer (NPA), and then they conclude that TAE bursts enhance the radial transport of fast ions [8]. In the experimental conditions similar to Ref. [8], the fast ion losses are observed directly by the scintillator lost ion probe (SLIP) [9], and some typical results are reported during the repetitive bursts of fast-ion losses synchronized with those bursts of TAEs in LHD [10].

In JT-60U, the reversed shear-AE induced fast ion redistribution is observed successfully from the neutron profile measurement [11]. However the diagnostics is difficult to distinguish between the redistribution and the loss clearly, and is no information on escaped fast-ion orbits on phase space.

In view of the characterization of redistribution and/or loss for fast ions in stellarator/heliotron system during the repetitive bursting TAEs, the fast ion losses are measured by the SLIP. The profiles of beam and thermal pressures are obtained from FIT code with plasma parameters of T_e, n_e, and an assumption of $T_i = T_e$. We make the progresses for understanding the fast ion confinements, transports, and losses in this paper.

2. Scintillator-lost ion probe (SLIP) on LHD

For the studies of fast-ion confinement and loss, the scintillator-lost ion probe has been designed and was installed into a new location of LHD. The toroidal location of SLIP is shown in FIG. 1. The SLIP consists of a periscope with eyepiece, relay, and objective lenses to transmit the scintillator light to the outside of the vacuum vessel. The transmitted light is divided into two paths; one is introduced into an image intensified charge coupled device camera (ICCD camera) and another 3x3 photomultiplier arrays. The scintillator of Ag:ZnS deposited on the glass plate is mounted inside the SLIP head. The fast ions enter into the SLIP head from the small aperture and hit the scintillator surface. The basic head structure is the same as the previous one mentioned in Ref. [9].

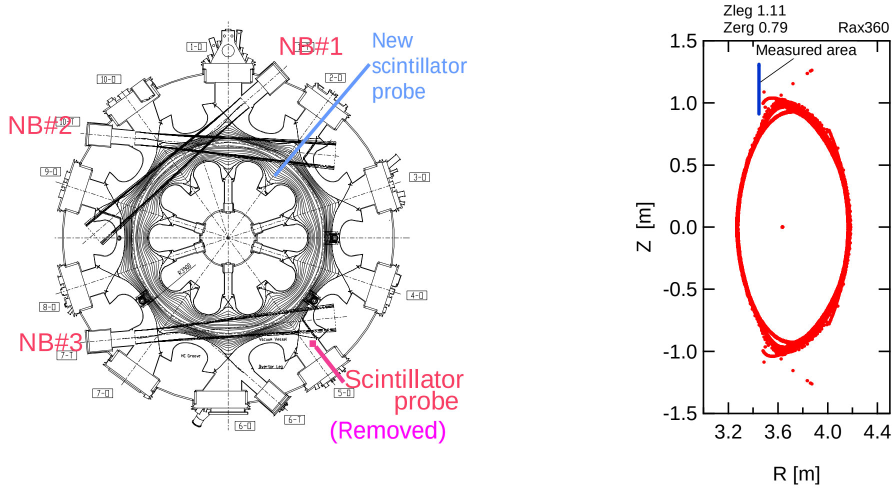

FIG. 1. Left: top view of LHD. The previous and the new installed SLIPs are drawn. The previous SLIP has already removed. Right: The cross sectional view of the ergodic layer of LHD is plotted with the location of the tip of new SLIP

The SLIP head is located outside the ergodic layer drawn in the right side of FIG. 1. The SLIP head is located at the inboard side of the vertically elongated poloidal cross section of LHD. The aperture is directed to the plasma. The diagnostic position can move to the vertical *z* direction by an air motor system. The SLIP can measure the flux, the pitch angle, and the velocity distribution of escaped fast ions at the edge region of the plasma.

2. Observation of bursting TAE induced fast ion losses

LHD equips with unique negative ion based neutral beam injectors (N-NBs) at E_b of ~190 keV, which satisfy the reactor relevant excitation conditions of Alfvén activities with the wide parameter range of υ_b/υ_A from 0.3 to ~ 4.0 at the relatively low toroidal magnetic field B_t = 0.75 T. The Alfvén activities for LHD discharges have been identified during N-NB heating and features have been characterized by sophisticated studies in Refs. [5-8]. FIG. 2 (a) shows the time evolution of plasma parameters, when we observe the repetitive bursts of Alfvén activities. FIGs. 2(b) and (c) show the spectrogram of the magnetic fluctuation and the fast ion loss signal I_{SLIP}, respectively, during bursting TAEs. The detected fast ion losses have the pitch angle ($\chi = \arccos(\upsilon_{//}/\upsilon)$) of ~ 130 degrees from the image monitored by the ICCD camera. In other time window, the n = 2 mode disappears, when the counter-injected NB2 with E_b of 160 keV is terminated. The bursting fast-ion losses have about every 5 ~ 10 ms intervals. The feature has the rise time of ~ a few hundred μs, which is almost the same rise time of magnetic fluctuations. The slow recovery time of 5 ~ 10 ms for fast ion loss signals in FIG.2(c) seems to be governed by n = 2 down chirping mode in FIG.2(b) until the subsequent burst starts.

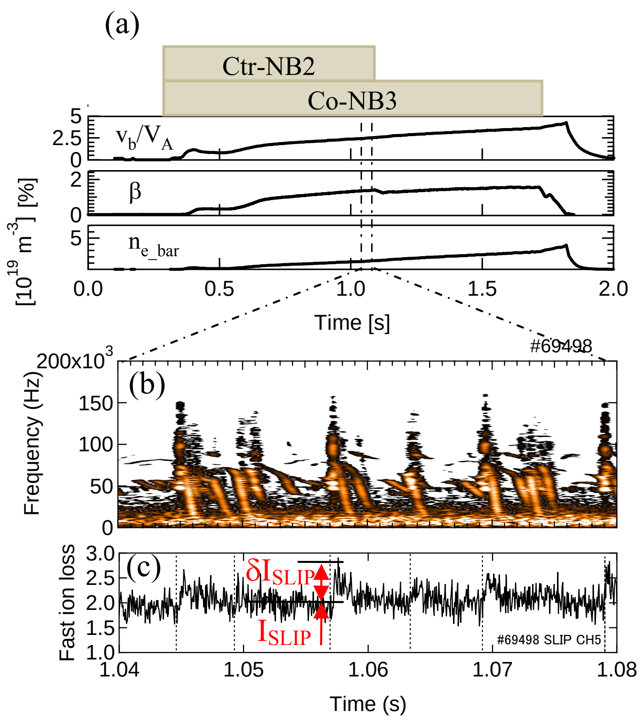

FIG.2. Time evolution of fast ion losses induced by repetitive TAE bursts for n = 1 at the robust frequency of ~50 kHz and n=2 at the frequency sweeping down from 80 to a few ten kHz. (a) Discharge waveforms for N-NBs, υ_b/υ_A, beta value, and line averaged density. (b) Spectrogram of magnetic fluctuations, (c) Fast ion loss signal I_{SLIP}. The difference of fast ion loss signal before and after TAE burst corresponds to δI_{SLIP}.

The effective confinement time of energetic ions τ^* was evaluated to be 2 ~ 3 ms during TAE bursts from the analysis of the degradation of stored energy W_p in Refs. [5, 7]. The TAE induced fast ion loss rate $\tau_{MHD}/\tau^* = 0.7/3.0 = 0.23$ at $t = 1.057$ s. On the other hand, the fast ion loss rate can be estimated to be $\delta I_{SLIP} / I_{SLIP} = 0.60$, which is much higher than τ_{MHD}/τ^*. Thus it is found that the loss location of fast ions is localized during TAE burst activities.

3. Global confinement from stored energy and local fast ion loss

We discuss the redistribution and the loss of fast ions from the experimental evidences. There is also a concern how to influence the confinement of thermal electrons and ions. In the discharge (shot #69494), the time evolution of plasma parameters is plotted in FIG. 3. At the discharge, the mode numbers for n = 1 and 2 are picked up from the Mirnov coil signals in FIG. 4. This time evolution can be separated into two time windows from 1.0 to 1.26 s and from 1.3 to 1.49 s, corresponding to hatched regions on the figure. The earlier and the latter time windows are dominated by n = 2, and n = 1, respectively.

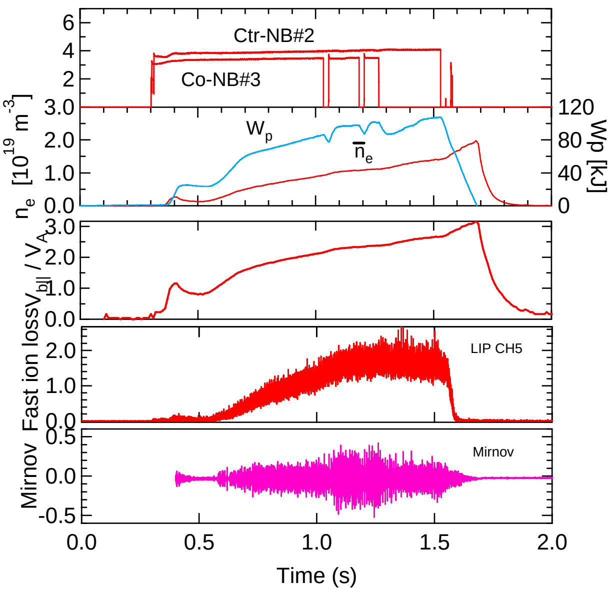

FIG.3. Time trace of LHD discharge #69494. From the top, NB injection wave forms, stored energy, line averaged electron density, υ_b/υ_A, fast ion loss signal measured by SLIP, and magnetic fluctuation are plotted.

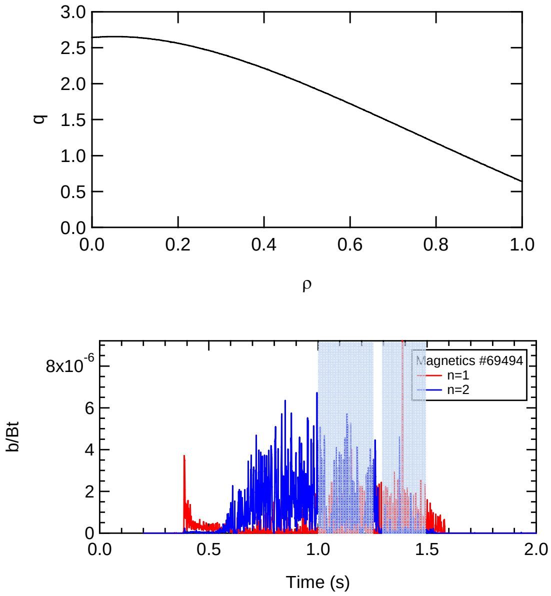

FIG.4. Upper graph shows the safety factor q profile for typical LHD configuration at R_{ax} = 3.6m in the case of β = 0. Magnetic fluctuations of n = 1 at t = 1.31 ~ 1.49 s and n = 2 at t = 1.0 ~ 1.26 s for LHD discharge #69494.

The correlation between the global confinement (or loss) and the local fast ion losses are discussed from the drop of the stored energy δW_p due to TAEs for n = 1 and 2 modes in FIG. 5 and the drop of the fast ion loss signal δI_{SLIP} in FIG. 6. Fast ion losses are enhanced during n = 1 dominant case, but not clearly observed during n = 2 dominant case (weak fast ion loss, so called redistribution), even though the degradation of W_p maintains the same level in both n = 1 and 2 mode cases. In addition, there is no strong correlation with the magnetic fluctuation strength. This result suggests the redistribution of fast ions for n = 2 case and the loss of fast ions for n = 1 case (the radial transport is theoretically pointed out in Ref. [12]), and fast ion loss is strongly correlated with the locations of TAE gaps and their structures.

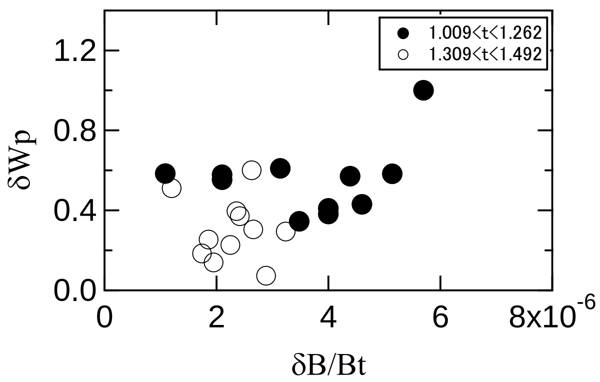

FIG.5. Loss of stored energy δW_p on the magnetic fluctuation level with n=1(open symbols) and n = 2(closed symbols) dominant TAE bursts.

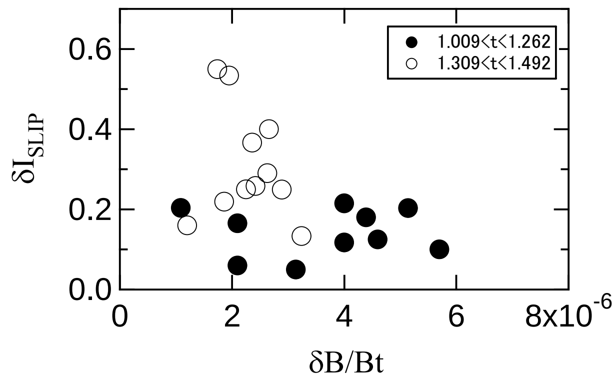

FIG.6. Dependence of TAE induced fast ion loss δI_{SLIP} on the magnetic fluctuation level with n = 1(open symbols) and n = 2(closed symbols) dominant TAE bursts.

During two time windows for n = 1 and 2 dominant cases, the pressure profiles for fast ions are calculated by the FIT code [13, 14]. As input plasma parameters of FIT code, measured T_e and n_e profiles are utilized with the assumption of $T_i = T_e$. These thermal components are defined as the bulk components. The results show that the bulk particle pressure transits from the peaked profile (n = 2 mode, FIG.7.) to the flattened profile (n = 1 mode, FIG.8.).

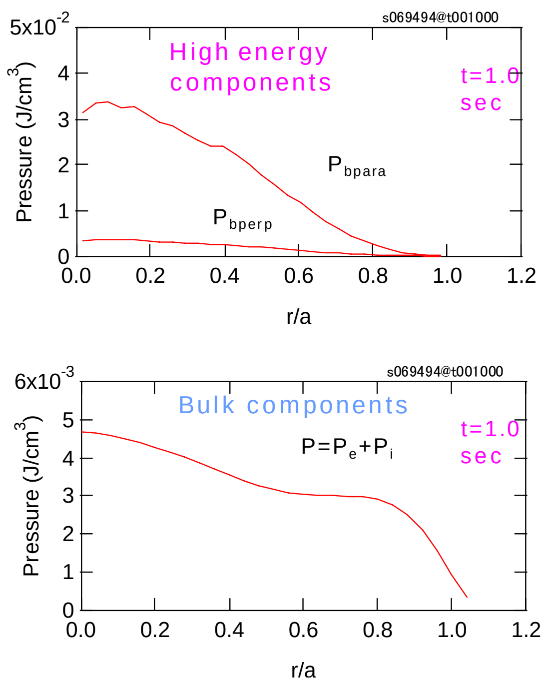

FIG.7. Fast ion pressure profiles for perpendicular and parallel components produced by co- and counter- NB injections obtained from FIT code. The lower graph shows the bulk (thermal) pressure profile obtained from measured T_e and n_e. The discharge #69494 is analyzed at t = 1.0 s.

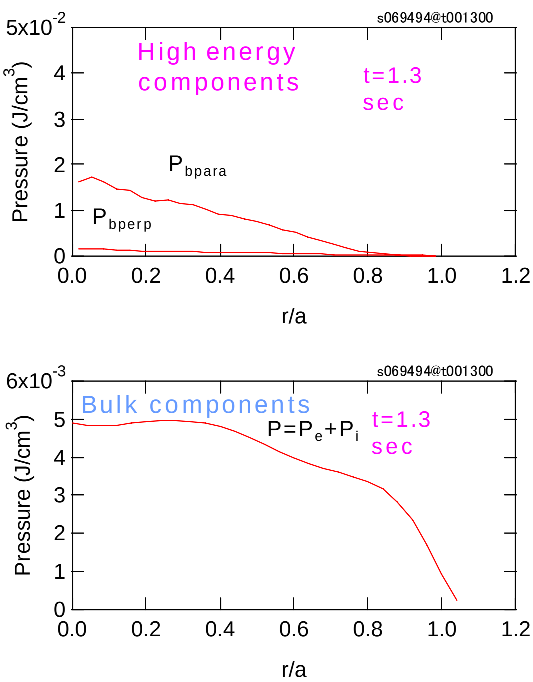

FIG.8. The discharge #69494 is analyzed at t = 1.3 s during counter NB injection. The bulk (thermal) component is affected and flattened during Alfvén activities, compared with that in FIG.7.

The distribution for bulk particles is affected strongly by TAE excitation. This feature is different from the case in Ref. [15], because they reported that the flattened profile is observed for the beam components, not for the bulk particles. The main reason that the beam pressure profiles are not flattened is considered that FIT code does not include the effect of Alfvén activities on the beam pressure profiles.

4. Instabilities - fast ion interaction and orbit loss of fast ions

For understanding fast-ion transports, the fast ion orbit is computed in backward time direction using the pitch angle χ = 130 degrees and fast ion energy E_b = 150 keV measured in FIG.9. This calculation can find out the origin of fast ions detected here. The fast ion, which starts at SLIP head, passes surely through the TAE gap locations. The interaction with disturbed fields due to TAE activities leads to a change of pitch angle as well as the subsequent fast ion loss near the boundary between confinement and loss on velocity space.

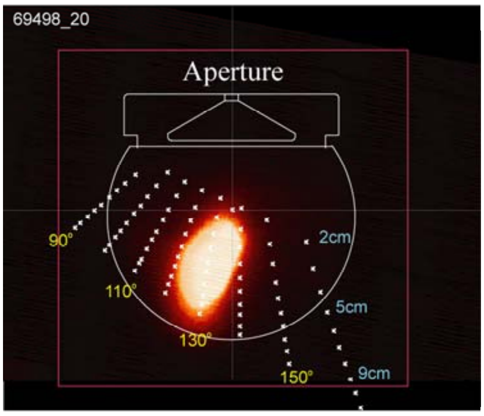

FIG.9. Fast ion loss on the scintillator for the discharge #69498 at t = 0.66 s. The pitch angle is around 130 degrees and gyro radii ~3-10 cm. This information is used to compute the fast ion orbit in backward time direction to find the origin of fast ions.

The repetitive bursts of TAEs are explained by the theoretical model, which so called "predator-prey" relationship [16]. The numerical simulation in tokamak has already been carried out [17], and then the predator- prey model behaves the similar repetitive bursts of TAEs. Our experiments would be described by the same physical picture. The NBs are injected to the plasma, and then the beam pressure profile of beam ions grows gradually and reaches the equilibrium of the beam pressure. The beam driven TAE changes the profile of the beam pressure, and this change leads to the fast ion loss. The lower beam pressure due to the fast ion loss can grow the beam pressure up to the equilibrium again. This loop is repeated during NB injection in the case of repetitive TAE bursts. This phenomenon is found to follow the fast ion redistribution and loss.

4. Conclusion

The fast ion losses are studied by the measurement of the SLIP in LHD in the presence of the TAE activities under the reactor relevant condition, $\upsilon_{b//}/\upsilon_A > 0.3 \sim 4$.

- From the magnetic fluctuations, the TAE frequencies of low n modes range from 50 to 100 kHz. During the repetitive TAE bursts, the rise time of fast-ion loss signal for one burst event is about less than 300μs. The burst interval is ~10ms. The repetitive bursts for fast-ion losses are correlated with the TAE bursts. Therefore the TAE activities exhaust the fast-ions toward outside of plasma confined region.

- The TAE induced losses (global losses (W_p) and fast ion losses (δI_{LIP})) are observed. TAE activities recognize two categories,
  - W_p degrades, following fast ion loss
  - W_p degrades, following no significant fast ion loss (redistribution)

  This feature is strongly related to the spatial structure of mode location of TAEs in plasmas rather than the beam pressure profile.

- The profile of bulk (thermal electron and ion) pressure is flattened during TAE bursts. At that time it is found that the resulting fast ion loss is enhanced. However since the SLIP diagnostics is local measurements, the careful analyses are still required.

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