Experimental observation of stabilization effect of AE bursts due to resonant interaction with fast ions in LHD plasmas

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The stabilization effect of bursting activities of Toroidal Alfvén Eigenmodes (TAEs) due to resonant interaction with fast ions was observed in LHD plasmas. During TAE bursts, the energy spectrum of fast ions was measured using a high-time-resolution Si-based Neutral Particle Analyzer (NPA). TAE bursts were categorized into growth and decay phases. In both phases, the gradient in fast ion energy spectra was reduced in the energy range where the resonance condition was satisfied. This observation suggests Landau damping of TAE by fast ions. It should be noted that Landau damping was identified even during the growth phase of TAE bursts.

Alpha particles generated by D–T fusion reactions serve as a self-heating source in fusion plasmas, and their good confinement is essential for sustaining a burning plasma [1]. However, it has been recognized that fast ions can resonantly interact with Alfvén eigenmodes (AEs), leading to enhanced transport and consequent particle losses, accompanied by a variety of nonlinear behaviors [2]. Therefore, a comprehensive understanding of wave-particle interactions between fast ions and AEs is crucial for accurate prediction and control of alpha particle confinement in burning plasmas.

Phase-space dynamics of fast ions are important for understanding interactions between fast ions and AEs. The radial gradient of the distribution function of fast ions destabilizes AEs and causes the radial redistribution. In contrast, the gradient in energy can stabilize AEs through Landau damping because it is typically negative due to the slowing-down process. The experimental investigation of the dynamics of fast ions in energy space has been limited compared to that in radial space, because of the time resolution of fast ion measurement.

The objective of our research is to investigate the dynamics of fast ions in energy space, particularly by resolving the temporal evolution of AEs and analyzing the associated phase-space dynamics. Utilizing the Large Helical Device (LHD), we have investigated the interaction between AEs and fast ions produced by tangential neutral beam injection (NBI).

Si-based Neutral Particle Analyzer (NPA), which has high time resolution, was utilized for fast ion measurement.

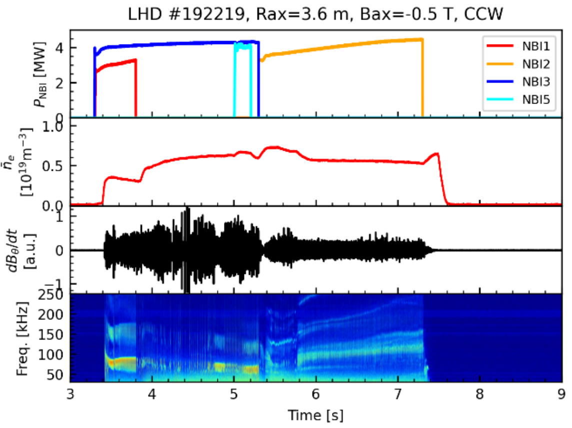

Figure 1: Typical discharge pattern of the present experiment. (a)NBI heating power. (b)Line-averaged electron density. (c)Magnetic fluctuation. (d)Spectrogram of the magnetic fluctuation.

LHD is one of the largest stellarator-type devices. The major/minor radii are 3.9 m/0.6 m, respectively, and a maximum operational magnetic field strength of 3.0 T. In the present experiments, magnetic field strength at the magnetic axis (Rax=3.6 m) was set to 0.5 T. Fast ions were generated by tangential NBI with injection energies up to 170 keV, making the produced fast ions super-Alfvénic. Figure 1 shows the typical discharge pattern of the present experiments. During NBI, strong activities of magnetic fluctuations in the Alfvénic frequency range were observed by magnetic probe arrays.

Fast ion measurement was conducted by Si-based Neutral Particle Analyzer (NPA). NPA measures energetic neutrals, which are produced by charge-exchange process between fast ions and neutrals in the plasma. Upgrade of electrical circuits enables us to measure fast ions with high time resolution (> 10 MHz), which is much higher than the typical frequency of AEs in the LHD plasmas (~100 kHz).

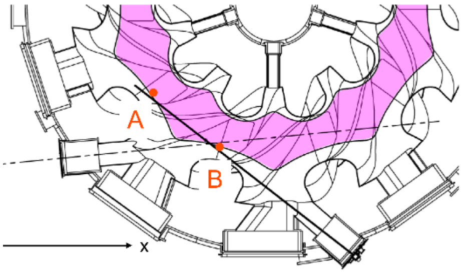

Figure 2: Schematic configuration of line-of-sight of Si-NPA (black line), and LHD plasma in vacuum configuration (pink shaded area). A and B correspond to those in figure 3.

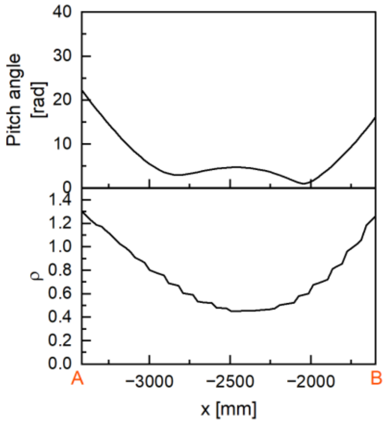

Figure 3: The distribution of pitch angle (upper) and rho (lower) along the line of sight (red-shaded area of left panels) in the present experiment. A and B correspond to those in figure 2.

The line of sight of NPA was designated to directly observe fast ions interacting with AEs. For this purpose, pitch angle and normalized minor radius (ρ) along the line of sight were optimized. The schematic configuration of the line of sight is depicted in figure 2. Figure 3 shows the distribution of pitch angle and ρ along the line of sight (between point A and point B). Since fast ions are produced by tangential NBI, the pitch angle of charge-exchanged energetic neutrals is expected to be small. Therefore, flux from the region where the pitch angle is small would be dominant. In that region, ρ is about 0.5-0.8. In LHD, AEs are typically destabilized around $0.5 \leq \rho \leq 0.8$. Thus, this line of sight enables us to observe the dynamics of fast ions interacting with AEs.

We focus on the period during which bursting activities in the AE frequency range are prominent, as shown in figure 4. The energy spectrum of energetic neutrals was continuously measured, as shown in the bottom panel. In this period, bursting activities around 50 kHz are dominant. From the phase-correlation analysis by magnetic probe array and calculation by STELLGAP code [3], the toroidal/poloidal mode numbers (n/m) of the dominant mode were evaluated as $|n| = 1$ (left panel of figure 5) and $|m|/|m+1| = 1/2$ (right panel of figure 5). These analyses indicate that observed bursting activities are Toroidal Alfvén Eigenmodes (TAE).

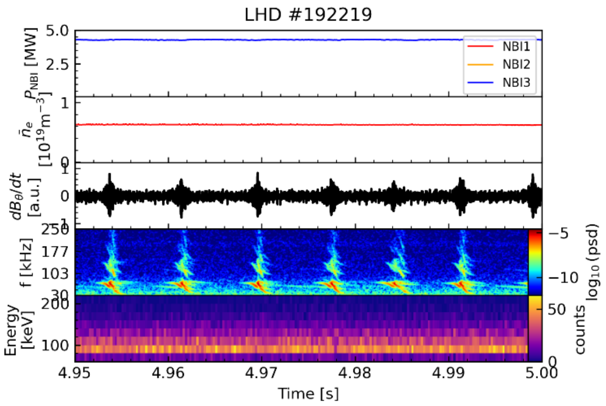

Figure 4: Zoomed-in view of figure 1. The top four panels are the same as figure 1. The bottom panel shows time evolution of energy spectrum of energetic neutrals.

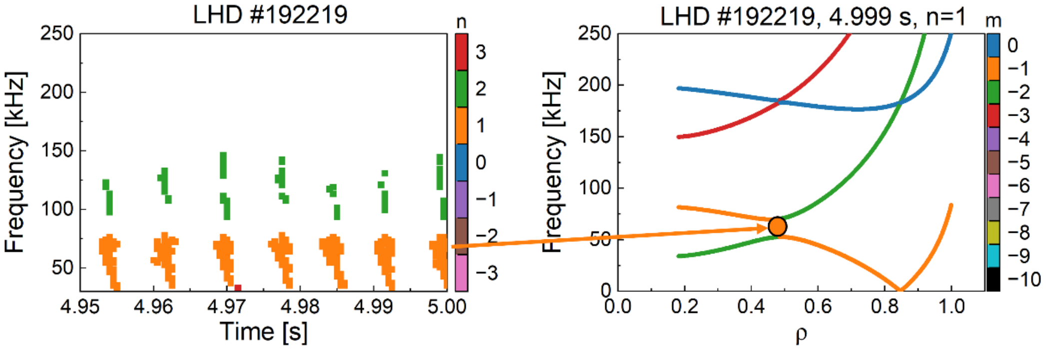

Figure 5: (left) Toroidal mode numbers of observed bursting activities. (right) Alfvén continuum calculated by STELLGAP code [3].

Modulation of energy spectra due to interaction with TAE bursts was analyzed with the conditional average technique. TAE burst is classified into growth/decay phases using the time evolution of the power spectrum calculated by Short-Time Fourier Transform (STFT). In this analysis, the growth/decay phase is defined as the period where the time derivative of the mode amplitude is positive and negative, respectively (figure 6).

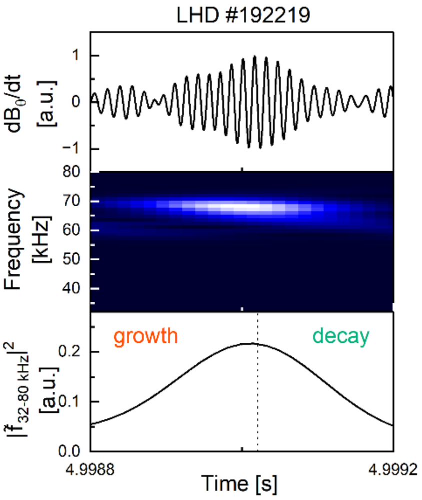

Figure 6: Time evolution of amplitude of measured magnetic fluctuation (top), spectrogram (middle), and power in the frequency range $32 \leq f$ [kHz] ≤ 80.

The upper panel of figure 7 shows the energy spectra of each phase which were conditionally averaged through 115 bursts. Energy spectrum in the reference phase, where TAE activities were negligible, is also plotted. In all phases, the gradient around 80-170 keV is negative. This result is consistent with the classical slowing down distribution. Then the gradient in energy of the distribution function of fast ions contributes to the stabilization of TAE bursts.

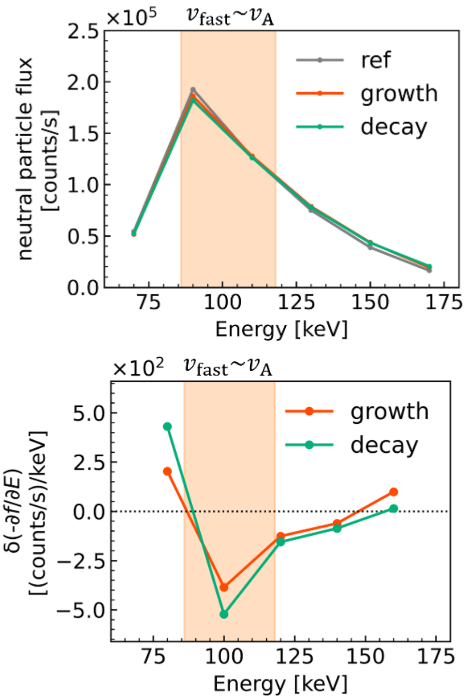

Figure 7: (Upper) Conditionally averaged energy spectra in reference (gray), growth (red) and decay (green) phase. (Lower) Difference of gradient in energy of energy spectra between growth and reference phase(red), and decay and reference phase(green). Orange-shaded area in both panels corresponds to the energy range where resonance condition is satisfied.

The lower panel of figure 7 shows the difference between the gradient in energy of growth/decay phases and that of the reference phase. In both phases, the gradient around 100 keV was locally reduced. To further investigation, we evaluated the resonance condition $v_{\mathrm{fast}}\sim v_{\mathrm{A}}$, where v_{fast} is the velocity of fast ions and v_{A} is the phase velocity of TAE bursts. v_{A} is evaluated from the TAE frequency and mode numbers. Using evaluated v_{A}, the energy range where the resonance condition is satisfied is plotted in figure 7 (orange-shaded area). The reduction of gradient occurred in the resonant energy range, which suggests that Landau damping of the TAE burst by fast ions was observed.

It should be noted that Landau damping was identified even during the growth phase of TAE. Whether TAE is destabilized or stabilized is determined by the balance between destabilization and stabilization. When TAEs are in the growth phase, the destabilization effect by fast ions should be prominent, because it is the only free energy source for the excitation of TAE in our experiment. This result suggests that fast ions simultaneously contribute to TAE bursts in two competing ways: destabilization through the radial gradient and stabilization through the gradient in energy.

References

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