Alfvén Eigenmodes and Geodesic Acoustic Modes Driven by Energetic Ions in an LHD Plasma with Non-monotonic Rotational Transform Profile

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Abstract

In the Large Helical Device (LHD), a reversed magnetic shear (RS) configuration having non-monotonic rotational transform profile was formed by intense counter neutral beam (NB) current drive. In the RS configuration helical plasma, the reversed shear Alfvén eigenmode (RSAE) with n=1 toroidal mode number was identified together with energetic-ion-driven geodesic acoustic mode (GAM) with n=0. Temporal sweeping of the RSAE frequency was well-explained by ideal MHD theory without introducing non-perturbative energetic ion effects. The minimum value of RSAE frequency in the sweeping phase agrees well with GAM frequency. Nonlinear interaction between the RSAE and GAM generates a lot of driven modes. In thus produced low density RS configuration, bulk ion temperature in the plasma center T_{io} starts to increase linearly in time for more than 10 times of global energy confinement time just after the local minimum of the rotational transform has passed through the particular rational value ι/2π=1/3. When energetic ion driven AEs and GAM are re-excited appreciably, T_{io} decreases with slower time scale than that of the rise. During the rising phase of T_{io}, plasma potential measured by heavy ion beam probe becomes deeper in the plasma core region. Then, it becomes shallow in the decay phase of T_{io}.

1. Introduction

In a burning plasma, the Alfvén eigenmodes (AEs) may be destabilized by alpha particles and then would enhance their radial transport and loss. Comprehensive understanding of interaction between AEs and energetic ions is particularly important for finding a way to minimize energetic ion transport induced by AEs or even use AEs favorably. So far, various AEs and their impacts on redistribution and loss of energetic ions are intensively studied in many tokamaks and helical devices [1-8].

Recently, *reversed magnetic shear* (RS-) configuration which has the zero magnetic shear layer away from the magnetic axis has received much attention because high plasma confinement with internal transport barrier (ITB) is easily achieved. In the RS-tokamak configuration, characteristic energetic-ion-driven Alfvén eigenmodes called *reverse shear AE (RSAE)* or *Alfvén cascade* are often observed [9-13]. Excitation of RSAE is closely related to the existence of zero magnetic shear layer in a non-monotonic safety factor (q-) profile. In most of cases, the RSAE frequency is swept upward from a finite minimum frequency when the local minimum q_{min} decreases passing through the integer values 3, 2 and so on in time. It was theoretically explained that the minimum starting frequency is determined by the geodesic curvature effect and other plasma pressure effects [14]. The RSAE frequency is used as a useful experimental monitor of $\mathrm{q}_{\mathrm{min}}$ and enables us to predict a timing of the formation of an internal transport barrier (ITB) [15].

It is interesting and significant to investigate energetic ion driven instabilities such as AEs and confinement properties of bulk plasma in RS-helical/stellarator plasmas with non-monotonic rotational transform profile. This experimental trial was carried out on the Large Helical Device (LHD) by using counter neutral beam (NB) current drive. This paper describes characteristic features of energetic ion driven MHD instabilities and bulk plasma confinement in thus produced reversed magnetic shear configuration on LHD.

2. Reversed Magnetic Shear Configuration Formed with Counter NB Current Drive

In low beta LHD plasmas, the rotational transform $\iota/2\pi$ increases monotonically toward the plasma edge, where the whole plasma region is in *negative* magnetic shear. In order to generate a non-monotonic rotational transform profile with a local minimum which is a *reversed shear* (RS-) helical configuration on the condition that energetic ion effect is noticeable, large amount of plasma current I_p up to $|I_p|/B_t$~100kA/T (B_t: toroidal magnetic field) was induced in low density plasma by counter neutral beam injection (NBI). A typical discharge waveform is shown in Fig.1, where I_p reaches -130 kA (counter direction) at B_t=1.3 T in the magnetic axis position in the vacuum R_{ax}=3.75m. Total absorption power of counter NBI is about 2 MW and typical energy of hydrogen beam is about 160 keV. In this shot,

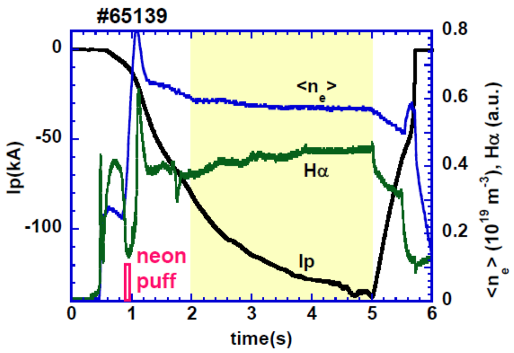

Fig.1 Typical time evolution of a plasma with large counter plasma current driven by NBI, where B_t=1.3T and R_{ax}=3. 75m.

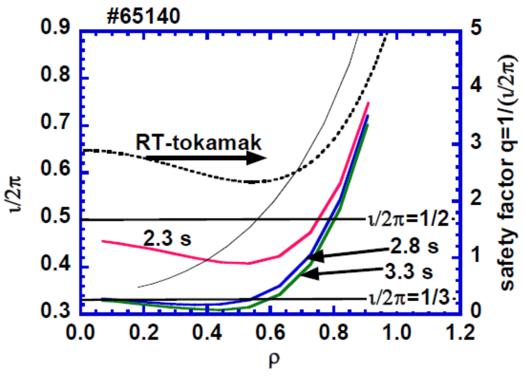

Fig.2 Time evolution of the rotational transform profiles measured by MSE(thick curves). Thin curve denote the $\iota/2\pi$ profile in the vacuum field. The dotted curve show an example of q-profile in a RT-tokamak.

neon gas was puffed into hydrogen plasma to minimize NBI power shine-through and electron return current. The line averaged electron density jumps up by neon gas puffing at t~0.9s, and is kept almost constant throughout a discharge, where the effective charge Z_{eff} is estimated to be ~ 6. Electron temperature profile keeps a parabolic shape having the central value T_{eo}~1.2 keV in the constant density phase (~2 s < t < ~5s). Electron density profile keeps a hollow profile having n_{eo}/n_{emax}~0.5 in the phase. Note that the parallel beam pressure due to energetic ions is typically ~3 times larger than the bulk pressure in the constant density phase. In this experimental campaign, the rotational transform profile was measure by motional-stark-effect spectroscopy (MSE). Time evolution of measured $\iota/2\pi$ profile is shown in Fig.2 for an almost identical shot with that shown in Fig.1. These data clearly indicate a RS-profile where the minimum appears around ρ~0.4-0.7 and the location moves inward slowly in time. The minimum value $(\iota/2\pi)_{\min}$ gradually decreases, passing through the rational values $(\iota/2\pi)_{min}$=1/2 and 1/3 (i.e., q_{max}=2 and 3). The rotational transform in the peripheral region is preferentially reduced by counter-flowing plasma current in the region, when the plasma current is rapidly increased by counter NBI in high electron temperature plasma of large averaged minor radius (~0.6m). This process transiently produces a non-monotonic rotational transform profile.

3. Characteristic MHD Modes Destabilized by Energetic Ions

In the RS-configuration plasma, two types of characteristic MHD modes were observed in various fluctuation diagnostics. Figure 3 shows a spectrogram of magnetic probe signal. As seen from Fig.3, one is n=1 mode of which frequency is swept downward to upward sequentially, via the minimum frequency. The other is n=0 toroidally symmetric coherent mode. The time evolution of the n=1 mode frequency is explained consistently by the mode frequency inferred from shear Alfvén spectra calculated by AE3D code [16] using the

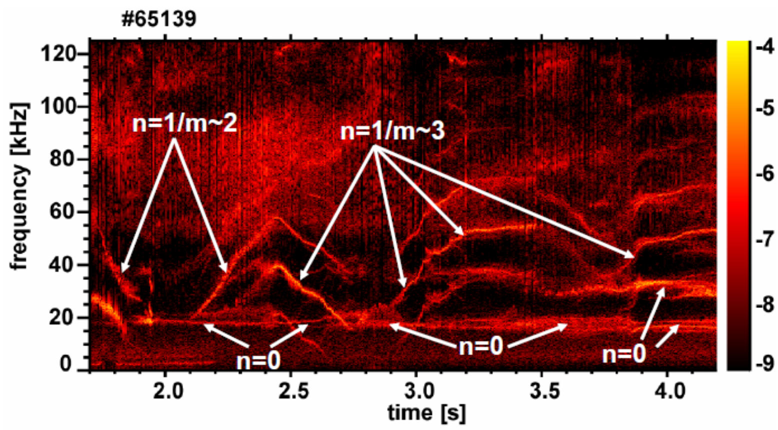

Fig.3 Spectrogram of a magnetic probe signal.

experimentally obtained rotational transform and electron density profiles (Fig.4). From these discussions, the n=1 mode has been identified as RSAE for the first time observed in a helical plasma [17]. This frequency sweeping in RSAE clearly indicates the realization of a non-monotonic *ι/2π* profile with a minimum away from the magnetic axis. The frequency of n=1 RSAE having m~2 (m: poloidal mode number) is swept downward till t~2.0s and then swept upward through the minimum (~18 kHz). The similar time evolution of the frequency of n=1/m~3 RSAE is also seen around t~2.75s. The observed minimum frequency agrees well with the geodesic acoustic mode (GAM) frequency estimated by the kinetic theory for helical plasmas as [18, 19], $f_{GAM} = \frac{C_{hel}}{2\pi R}\sqrt{\frac{T_e+(7/4)T_i}{C_Z m_p}}\sqrt{2+(\iota/2\pi)^2 F}$, where F and C_{hel} respectively denote correction factors dependent on T_e/T_i and helical field ripple, and are order unity. The factor C_z stands for an effective enhancement factor of hydrogen mass m_i due to heavier ion doping such as neon. In the evaluation of f_{GAM}, F~1, C_{hel}~1 and Cz~1.5 are adopted for the present experimental condition. This mentioned behavior of RSAE frequency is consistent with the theory developed for the RS-tokamak plasma [14]. Note that the frequency sweeping occurs downward and then upward sequentially, while it is uni-directional (upward) in most of RT-tokamak plasmas. This uni-directional sweeping was explained by energetic ion effects [9, 20].

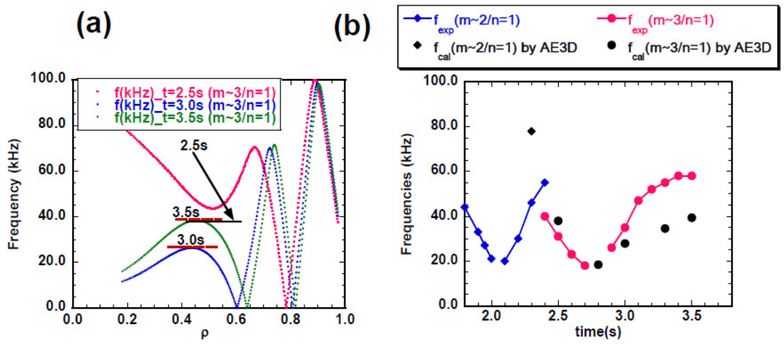

Fig.4(a) Shear Alfven spectra calculated by AE3D code for the RS plasma shown in Fig.3. (b) Comparison of RSAE frequency calculated by AE3D (black diamonds and circles) with experimental data (blue and red curves).

The other n=0 coherent magnetic fluctuations has almost constant frequency of ~18 kHz. The frequency is close to the minimum of the RSAE frequency and is comparable to the GAM frequency. The frequency reflects the change in electron temperature T_e. Figure 5 shows an example where the frequency of n=0 mode decreases, responding to the decrease in T_e due to cold gas injection, although the dependence on T_e seems to be stronger than $\sqrt{T_e}$ -dependence. The spectrum is split into 2 - 5 spectral lines having n=0 in the latter phase of t >3.1s. This is a typical feature of nonlinear effects in energetic ion driven modes [2, 21]. From these investigations, this n=0 mode is thought to be GAM excited by energetic ions. This is similar to the n=0 mode observed in JET tokamak plasma, which was called global GAM [22]. It should be noted that the potential fluctuation amplitude of GAM measured by heavy ion beam probe reaches up to ~0.8 kV. So far, the excitation mechanism is not fully understood.

Information of the internal structure of these modes was derived by the correlation analysis between electron cyclotron emission (ECE) signals and magnetic probe (MP) signal. In this experimental campaign, electron temperature fluctuations were not derived because of very weak fluctuation level. Radial profiles of the coherence between ECE and MP data γ^2_{XY} and the phase θ_{XY} for m~3/n=1 RSAE at t~2.5s are shown in

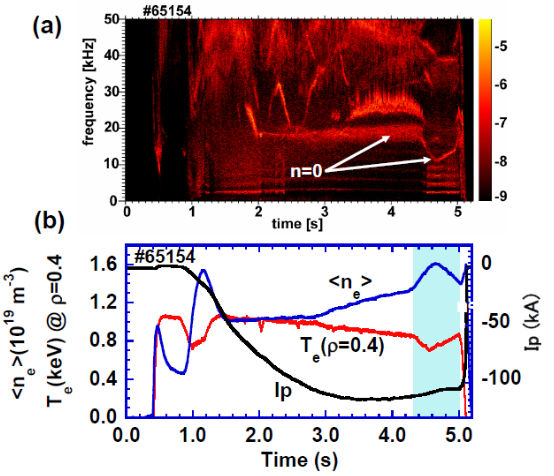

Fig.5 (a)Spectrogram of magnetic probe signal in a RS-plasma with the decrease in n=0 mode frequency. (b) Time evolutions of electron temperature at ρ=0.4, line averaged electron density and plasma current.

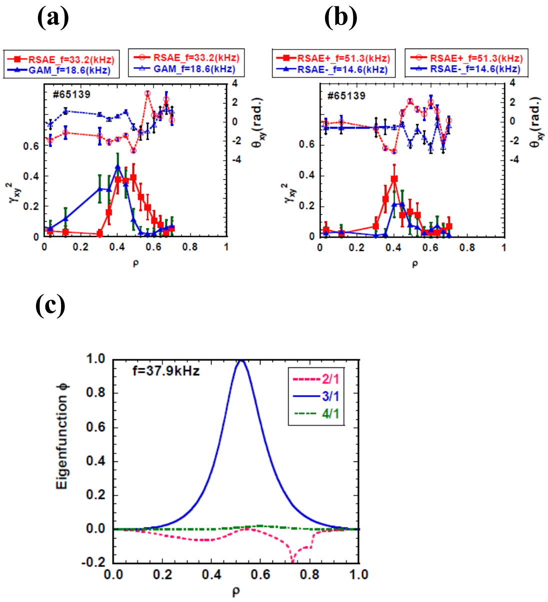

Fig.6(a) Radial profiles of the coherence γ^2_{XY} and θ_{XY} for the m~3/n=1 RSAE and n=0 GAM at t~2.5s. (b)Radial profiles of γ^2_{XY} and θ_{XY} for the satellite modes with f_+ and f_- , which are driven by nonlinear coupling between RSAE and GAM. (c) Eigenfunction of electrostatic potential for m~3/n=1 RSAE calculated by AE3D code.

Fig.6(a). The γ^2_{XY} has a clear peak around ρ~0.4. This suggests that the eigenfunction of the radial displacement ξ_r of RSAE has a peak around ρ~0.4, because the electron temperature fluctuation caused by shear Alfven wave will be expressed as $\tilde{T}_e \approx -\frac{\xi_r}{T_e}\frac{\partial T_e}{\partial r}$. An eigenfunction of electrostatic potential for RSAE calculated by AE3D code is shown for the plasma at t=2.5s in Fig.6(c). This shape is consistent with the experimental data shown in Fig.6(a), because the radial displacement induced by AEs will be approximately expressed as $\xi_r \sim -\frac{m}{\omega B}\frac{\phi}{r}$.

In Fig.6(a), γ^2_{XY} and θ_{XY} for GAM are also shown. The eigenfunction is inferred to be extended slightly to the interior region, compared with RSAE. Note that both RSAE and GAM overlaps at ρ~0.4 and are expected to couple each other nonlinearly. Actually, other chirping modes of which frequencies are shifted by the GAM frequency are identified in Fig.3, and are thought to be excited through nonlinear coupling between the RSAE and GAM. All these chirping modes have n=1, because GAM has n=0 and the RSAE has n=1. Selection rules for the frequency and toroidal mode number are satisfied among the RSAE, GAM and the other mode excited by nonlinear coupling. This fact indicates obvious three-wave coupling among them. The radial profiles of γ^2_{XY} and θ_{XY} for thus driven modes with $f_+ = f_{RSAE} + f_{GAM}$ and $f_- = f_{RSAE} - f_{GAM}$ are shown in Fig.6(b). It is seen that they are also localized around RSAE and GAM.

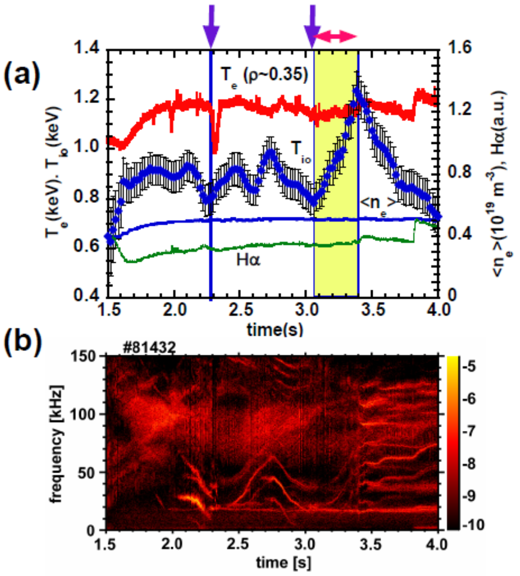

Fig.7 (a) Time evolution of the central ion temperature, electron temperature at ρ~0.35, line averaged electron density and H_α-emission in the RS configuration. The yellow zone indicate the T_{io}-rise phase. (b) Spectrogram of magnetic probe signal.

4. Bulk Plasma Behaviors

In the RS-tokamak plasma, the rational surface at the zero magnetic shear layer that separates negative and positive shear region attracts much attention because zonal flow may be easily induced in such peculiar region and may trigger the formation of internal transport barrier. We have also investigated behaviors of bulk plasma in the RS-configuration of LHD, and found an interesting signature of bulk ion and electron temperatures. In the RS plasma, the central electron temperature T_{eo} measured by ECE polychromator has a small dip when $(\iota/2\pi)_{min}$

passes through the rational values (=1/2 and 1/3) (Fig.7). In particular, when $(\iota/2\pi)_{min}$ passes 1/3, the central ion temperature T_{io} measured by soft X-ray crystal spectrometer starts to increase continuously from t~3.05s for ~0.35 s for the time scale much longer than the global energy confinement time(~20ms), and reaches the peak value (~1.2 keV) of about 1.5 times larger than the initial value. This T_{io}-rise may link to an ITB formation. However, the rise is suddenly terminated by re-enhanced AEs. The data in Fig.7 have some similarities to the results in DIII-D [15]. In this special shot, time evolution of plasma potential profile was measured by heavy ion beam probe. Figure 8 shows the time evolution of the change of electrostatic potential for the potential averaged over t=2.0s to 2.1s. This indicates that the potential around the plasma center becomes deeper for the time interval from t=3s to t=3.4s. After that, the potential difference gradually decays with the decrease in T_{io}. It is speculated that the enhanced AEs may modify energetic ion orbits and then affect the potential profile.

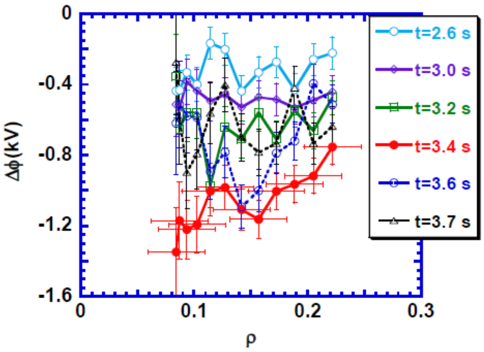

Fig.8 Time evolution of the change of plasma potential for that averaged over t=2.0-2.1s measured by heavy ion beam probe, in a RS plasma with the linear rise in T_{io}.

5. Summary

The reversed magnetic shear configuration where the zero magnetic shear layer exists away from the magnetic axis was realized by intense counter NB current drive. The rotational transform profile with a local minimum was confirmed with MSE diagnostics. The RSAE with characteristic frequency sweeping and GAM which are excited by energetic ions were simultaneously detected by magnetic probe array and other fluctuation diagnostics. The time evolution of RSAE frequency and radial structure of RSAE are explained very well with ideal MHD theory. The observed GAM has somewhat global structure in contrast to GAM induced by drift wave turbulence. Thus produced RS-configuration plasma sometimes exhibits a signature of ITB formation in ion temperature or anomalous ion heating. Underlying mechanisms in observed time behaviors of T_{io} , plasma potential and GAM should be clarified as an important future work.

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