ALFVÉN EIGENMODES AND THEIR IMPACT ON PLASMA CHARACTERISTICS IN JT-60U

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Abstract

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In weak or reversed magnetic shear plasmas of JT-60U, the excitation and the stabilization of Alfvén eigenmodes and their impact on energetic ion confinement were investigated with the negative-ion-based neutral beam injection at 330-360 keV. Toroidicity-induced Alfvén eigenmodes (TAEs) were observed in weak shear plasmas with $<\beta_h>\geq 0.1\%$ and $0.4\leq v_{b||}/v_A \leq 1$. The stability of TAEs is consistent with the predictions by the NOVA-K code. New burst modes and chirping modes were observed at a higher beta regime of $<\beta_h>\geq 0.2\%$. The effect of TAEs, burst modes and chirping modes on the fast ion confinement is small so far. The strongly-reversed shear plasma with the internal transport barrier suppresses Alfvén eigenmodes.

1. Introduction

Weak or reversed magnetic shear is important for advanced tokamak operation because the safety factor profile with a weak or reversed shear region is compatible to a hollow current density profile formed by high bootstrap current [1]. However, big uncertainty is collective energetic particle effects in advanced tokamak modes. Especially, Toroidicity-induced Alfvén eigenmodes (TAEs) have the lowest damping [2, 3]. The stability of AEs depends strongly on q-profile [4, 5]. Actually, alpha-particle-driven TAEs were observed for central alpha particle beta as low as β_α~0.02% in weak shear DT plasmas on TFTR [6]. In the ion cyclotron range of frequency (ICRF) heating of JT-60U reversed shear plasmas, TAEs were stable for strongly-reversed shear plasmas with a steep density gradient formed by the internal transport barrier (ITB) [7, 8].

On JT-60U, the negative-ion-based neutral beams (NNB: ≤500 keV, ≤10 MW) [9, 10] can produce a peaked profile of fast ions and high fast ion beta of ~1% can be obtained. Furthermore, JT-60U has a capability of shaping control and q-profile control utilizing reversed shear operation [11, 12]. In recent experiments, AEs have been investigated intensively with the NNB injection into weak or reversed shear plasmas for controlling AEs in advanced tokamak modes. This paper presents these new results. The Alfvén eigenmodes' experiment with the NNB is mentioned in Section 2, the NNB-driven TAEs are described in Section 3, burst and chirping modes excited with the NNB are given in Section 4, stabilization of TAEs in strongly-reversed shear plasmas is presented in Section 5 and Section 6 summarizes this paper.

2. Alfvén eigenmodes experiment with NNB

The plasma configuration used in this series of experiments and two NNB beam lines are shown in Fig. 1. The toroidal magnetic field was selected to be 1.2-1.7 T for weak shear discharges and 2.1 T for reversed shear discharges. The low field operation can increase a ratio $v_{b||}/v_A$ ($v_{b||}$: the velocity of beam ions in the direction of the toroidal magnetic field, v_A: the Alfvén velocity), which is one of the important parameter for the TAE excitation. The ratio $v_{b||}/v_A$ could be increased up to 0.95 by increasing electron density. The safety factor at the plasma surface was in a range of 4.7-5.5. The NNB power of 2-4 MW was injected at 330-360 keV into deuterium or helium plasmas. The volume-averaged fast ion beta $<\beta_h>$ increased up to ~0.6% and the hot ion beta in the core region increased up to ~2%. In Fig. 1, the upper beam line passes near the center of the plasma and the lower beam line is shifted ~0.3 m away from the plasma center. By selecting one of two beam lines, pressure profile of NNB ions can be modified. The safety factor profile indispensable for the AE studies was measured with the motional Stark effect spectroscopy [13].

3. Toroidal Alfvén eigenmodes (TAEs)

Figure 2 shows the TAEs observed during the NNB injection. Time traces of plasma current I_p, line-averaged electron density $\overline{n}_e$ and the NNB power P_{NNB} are shown in the top figure. The NNB of 1.5-2 MW was injected at 360 keV into the helium plasma during the current ramp-up. The sawtooth could not be observed during the NNB injection and it means that the safety factor at the center was higher than unity. As shown in a frequency spectrum of magnetic fluctuations in the bottom figure, TAEs with toroidal mode number n=1 and n=2 were observed. The n=2 mode appears first and the n=1 modes follows. Solid curves in the frequency spectrum show the TAE frequency calculated with the line-averaged electron density $\overline{n}_e$ and the toroidal magnetic field on axis B_{t0} ($f_{TAE} \quad B_{t0} / \sqrt{2\overline{n}_e}$). Measured mode frequency can be well explained by assuming safety factor q of 1.5 for the n=1 mode and 1.75 for the n=2 mode. A ratio $v_{b||}/v_A$ is in a range of 0.4-0.7 during the appearance of TAEs. The volume averaged hot ion beta $<\beta_h>$ was evaluated to be ~0.09% using the Orbit-following Monte-Carlo (OFMC) code [14]. This beta value is consistent with the threshold β_α in the weak shear DT discharge on TFTR [6] and about one-fifth to one-tenth the threshold value for excitation of TAEs with tangential neutral beams in TFTR [3] and DIII-D [15, 16] positive shear plasmas. It should be noted that TAEs disappear before the turn-off of the NNB and the TAE is stable for later beam injection. In Fig. 2, TAEs persist for 0.2-0.35 s, in contrast to burst TAEs lasting a few millisecond in TFTR [14] and DIII-D [17]. In the case of Fig. 2, the TAE amplitude is saturated at $\tilde{B}$~10^{-8} and the saturation of the TAE amplitude is considered to be due to the small fast ion drive by low fast ion beta.

Figure 3 shows a domain of TAE mode excitation in a space of the internal inductance l_i [=2(Λ-β_p)] versus $v_{b||}/v_A$ for H^0-NNB injection into helium plasmas. Filled circles and squares present cases of the n=1 mode and the n=2 mode excitation, respectively. Open squares show cases without TAE excitation. The NNB power and the line-averaged electron density was in a range of 1.9-2.6 MW and (0.28-0.89)×10^{19} m^{-3}, respectively. It is indicated that the n=1 and the n=2 TAEs are unstable for l_i≤1 and that the TAE is stable for l_i ≥1 regime even for higher NNB powers. A magnetic shear effect and/or the miss-alignment of TAE gaps with high pressure gradient region of fast ions are considered to be the stabilizing mechanism. In Fig. 4 (a), the Alfvén continuum spectrum for the n=2 mode calculated using the NOVA-K code and a profile of the safety factor at 4.8 s in the discharge presented in Fig. 2 are shown. The measured TAE frequency is presented with a dotted line. It is shown that the TAE gap is well aligned over the minor radius and the TAE is considered to be excited in the gap located r/a~0.6. The TAE gap is well aligned also for the n=1 mode and the location of the gap is at r/a~0.3. The locations of the n=1 mode and n=2 mode coincide with the region where a large pressure gradient of NNB ions is formed on a fast ion pressure profile and $\omega_{*f} \geq \omega_{TAE}/2$, which is the necessary condition for TAE excitation, is satisfied (ω_{*f} is the diamagnetic drift frequency of fast ions). As shown in Fig. 4 (b), the TAE frequency intersects the Alfvén continuum for a lower value of q_0=1.2 because a new TAE gap is created at r/a=1.25. It indicates that TAE can be stable due to the miss-alignment of the TAE gap. The relation between the Alfvén continuum and the measured frequency for q_0 suggests that the stability is sensitive to q_0 and the tendency of TAE excitation only in a low l_i regime can be understood from decreasing q_0.

4. Burst modes and chirping modes

New burst modes and chirping modes (the mode which frequency changes large) were found in a high beta regime of $<\beta_h>$≥0.2%. Figure 5 shows a typical discharge where burst modes and chirping modes were observed simultaneously with TAEs and EAEs (Ellipticity-induced Alfvén Eigenmodes). In a top figure of Fig. 5, temporal behavior of P_{NNB}, beam power for MSE, $v_{b||}/v_A$ and $\overline{n}_e$ are shown. The D^0-NNB of 360 keV is injected with the power of 4 MW into deuterium plasma . The central magnetic field is 1.2 T. The ratio $v_{b||}/v_A$ increased up 0.95 with the electron density. Here, the slowing down time of NNB ions τ_s is ~0.3 s. The frequency spectrum of magnetic fluctuations is shown in a bottom figure. Burst modes start in a early phase of the NNB injection (~0.1 s after the start of NNB), however, the activity is weak. When the fast ion beta increases and the safety factor at the center decreases, the activity of the burst mode becomes strong. The volume-averaged beta of NNB ions is $<\beta_h>$~0.5% and q_0~1.4 at 4.05 s. A burst mode occurs in a few millisecond with ~10 ms interval. The mode frequency changes ~20 kHz rapidly during the burst. The mode clearly seen for 4.1-4.57 s in a range of 57-58 kHz is the n=3 TAE and weak TAEs with n=1-3 are detected in a range of 60-70 kHz though they are not clear in the frequency spectrum. We can see that the burst modes are in a range of $\omega \leq \omega_{TAE}$. In a case, a mode burst starts with the n=2 mode, and this mode seems to trigger the n=1 mode with lower frequency, which causes the mode burst to terminate. The pressure profile of NNB ions was modified by selecting one of two beam lines shown in Fig. 1. The calculated pressure profiles are shown in Fig. 6. A peaked pressure profile in the central region is obtained with the top beam line and the hollow profile is produced with the bottom beam line. In a range of r/a≥0.4, the pressure is almost the same. The burst modes are strong for the peaked pressure profile. Meanwhile, they are very weak for the hollow pressure profile. Therefore, the high fast ion pressure in the central region and/or the high pressure gradient are considered to be responsible for the burst mode excitation.

Figure 7 shows the temporal behavior of magnetic fluctuation and the neutron emission rate when a burst mode appears. The amplitude of magnetic fluctuations of the burst modes is a few to ten times as large as that of TAEs and EAEs typically. A (2-3)% drop in the neutron emission rate is induced by the burst modes. This small drop indicates that the loss of co-injected NNB ions is small. On the other hand, fast ion loss correlating with TAEs and EAEs is not clearly observed due to the weak fast ion drive so far.

A strongly chirping mode of n=1 is detected during 3.8-4.1 s as shown in Fig. 5. The frequency chirping starts at ~30 kHz, which is about a half of the TAE frequency, and the frequency chirps up to the TAE frequency. The Alfvén continuum for the n=1 mode, the measured q-profile and the mode frequency at the start of chirp (3.8 s) and at the end of chirp (4.05 s) is shown in Fig. 8 (a) and (b), respectively. We can see that the measured frequency at the start of chirp is well inside the Alfvén continuum and it is in the TAE gap at the end of chirp. This chirping phenomena is similar to that observed in the ICRF heating of weakly-reversed shear plasmas in JT-60U [8]. It should be remarked that a large frequency chirping in Fig. 5 can be observed only in approximately τ_s after the start of the NNB injection, where the bump-on-tail is formed.

5. Stabilization of Alfvén eigenmodes in strongly-reversed shear plasma

It has been found that a reversed shear plasma with internal transport barrier (ITB) is immune to TAEs driven by energetic ions produced with the ICRF heating [7, 8, 18]. The TAEs have been observed only in weakly-reversed shear plasmas with moderate ITB formed after sequential collapses. In recent experiments, the excitation and stabilization of TAEs in reversed shear plasmas were investigated by injecting the NNB into 2.1 T deuterium plasmas. It was confirmed that a strongly-reversed shear plasma is stable for AEs.

Figure 9 shows profiles of the safety factor, the electron density and the beta vale of NNB ions in the case without exciting AEs. The safety factor profile has a minimum (q_{min}) at r/a~0.7-0.8 and is strongly reversed inside the location of q_{min}. Because of the ITB formation in the electron density, a slight jump in the density profile is observed just inside the location of q_{min}. The β_h profile shows that most of all NNB ions is deposited inside the ITB. The volume averaged fast ion beta $<\beta_h>$~0.28% is sufficiently higher than the threshold $<\beta_h>$~0.1% for TAE excitation. However, the fast ion beta is low and the pressure gradient is small in the low shear region around q_{min}. The miss-alignment between the AE gap and a region of the high pressure and large pressure gradient of NNB ions is considered to be the reason of the stabilization of AEs in the strongly-reversed shear plasma.

On the other hand, the n=1 TAE was observed in a weakly-reversed shear plasma as shown in Fig. 10 (a). Profile of q, n_e and β_h are presented in Fig. 10 (b). The q_{min} is located at r/a~0.6 and the ITB in the electron density can be seen at around r/a~0.4-0.5. The pressure profile of NNB ions is similar to that in the case of the AE stabilization except for r/a≤0.3. The relation between the Alfvén continuum and measured TAE frequency indicates that the n=1 TAE is excited at a TAE gap formed at r/a~0.5, where magnetic shear is weak and the fast ion beta is as high as ~1%. The TAE is excited because of the well-aligned TAE gap.

The excitation condition of Alfvén eigenmodes and burst modes by injecting the NNB in JT-60U is plotted in a space of $v_{b||}/v_A$ against $<\beta_h>$ in Fig. 11, comparing with a domain where TAEs exhibiting burst activity have been observed in positive shear plasmas of TFTR and DIII-D and and domain where alpha-particle-driven TAEs in TFTR have been excited in weak shear plasmas. The TAE starts to be excited at $<\beta_h>$~0.1% in a weak shear plasma and the beta value is comparable to the threshold for TAE excitation by alpha particles in TFTR weak shear plasma. In a regime of $<\beta_h>\geq 0.2\%$, burst modes is excited in addition to TAEs and EAEs. The TAE is also excited for $<\beta_h>$~0.3% in a weakly-reversed shear plasma, however, TAEs become stable in strongly-reversed shear plasmas with similar beta value. This plot also shows that not only macroscopic parameter as $<\beta_h>$ but also local parameters such as magnetic shear and pressure gradient of hot ions are important for understanding AE excitation and stabilization.

6. Summaries

The excitation and stabilization of AEs in weak or reversed magnetic shear plasma were investigated with the NNB injection at 330-360 keV. The TAEs were observed in weak shear plasmas with $<\beta_h>\geq 0.1\%$ and $0.4\leq v_{b||}/v_A\leq 1$. The threshold $<\beta_h>\geq 0.1\%$ is as low as threshold β_α in weak shear TFTR discharge. The TAEs are stable in a high l_i regime of $l_i\geq 1$ for $<\beta_h>$~0.1%. The excitation and stabilization is consistent with predictions by the NOVA-K code. New burst modes and chirping modes were observed at higher beta of $<\beta_h>\geq 0.2\%$. A burst modes occurs in a range of $\omega\leq\omega_{TAE}$ and the mode frequency changes rapidly by ~20 kHz in a burst of a few millisecond. The amplitude of burst modes is a few times to ten times as large as that of TAEs and EAEs. A few percent drop in the neutron emission rate was observed correlating with the burst modes. Fast ion loss correlating with TAEs and EAEs was not clearly observed due to the weak fast ion drive. The chirping modes appear in a early phase of the NNB injection and the mode frequency starts to chirp from inside the Alfvén continuum and increases up to the TAE frequency. This chirping modes are excited only in a duration of the slowing-down time of NNB ions after the start of the NNB injection. In the strongly-reversed shear plasma with the ITB, AEs were suppressed. It is considered to be due to the miss-alignment of the AE gap and/or the low pressure gradient and low fast ion beta in a low shear region.

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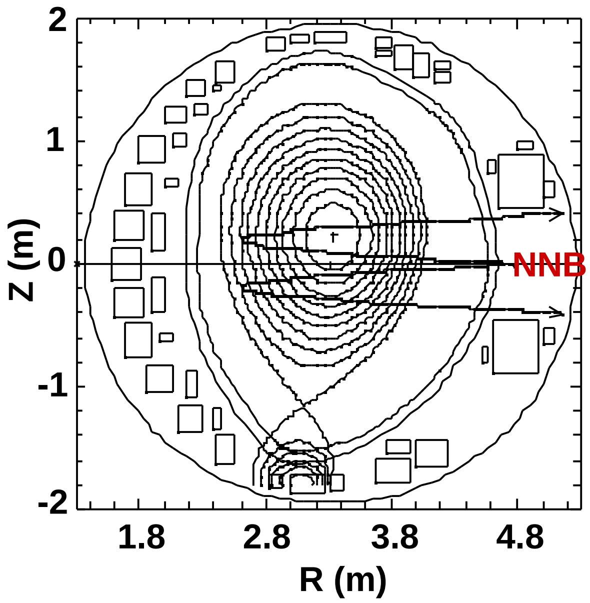

FIG. 1. Plasma configuration and two beam lines of negative-ion-based neutral beams (NNB) are shown. The NNB of 2-4 MW was injected at 330-360 keV.

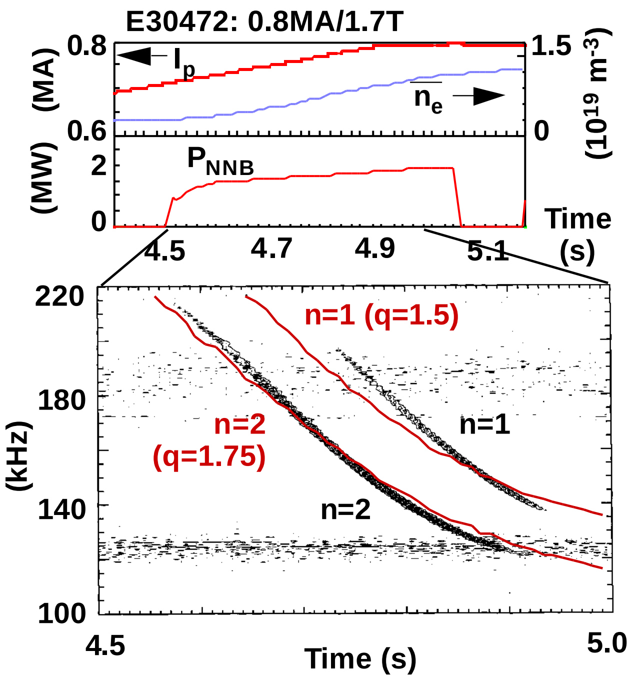

FIG. 2. Time traces of plasma current I_p, line-averaged electron density $\overline{n_e}$ and NNB power P_{NNB} are shown (top). The H^0-NNB was injected at 360 keV into helium plasma. B_{t0} = 1.7 T and I_p=0.8 MA at a flat top. NNB-driven TAE modes with toroidal mode number of n=1 and n=2 (bottom). TAE mode frequencies calculated with $\overline{n_e}$ and B_{t0} are also shown with solid lines.

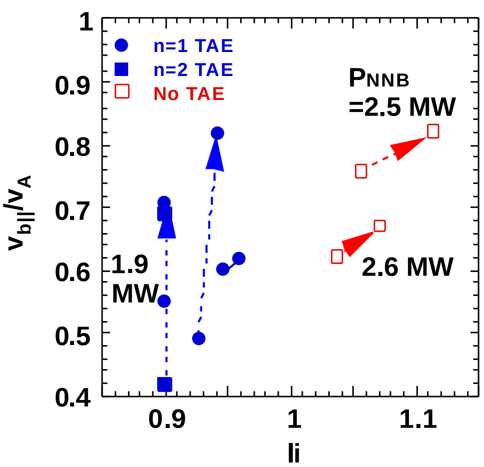

FIG. 3. A domain of TAE mode excitation in a space of internal inductance li v.s. $v_{b||}/v_A$ ($v_{b||}$:velocity in the magnetic field direction defined at the magnetic axis, v_A:Alfvén velocity) for H^0-NNB injection into helium plasmas. Filled circles show n=1 mode excitaion, filled squares show n=2 mode excitaion. Open squares show the cases without TAE excitation.

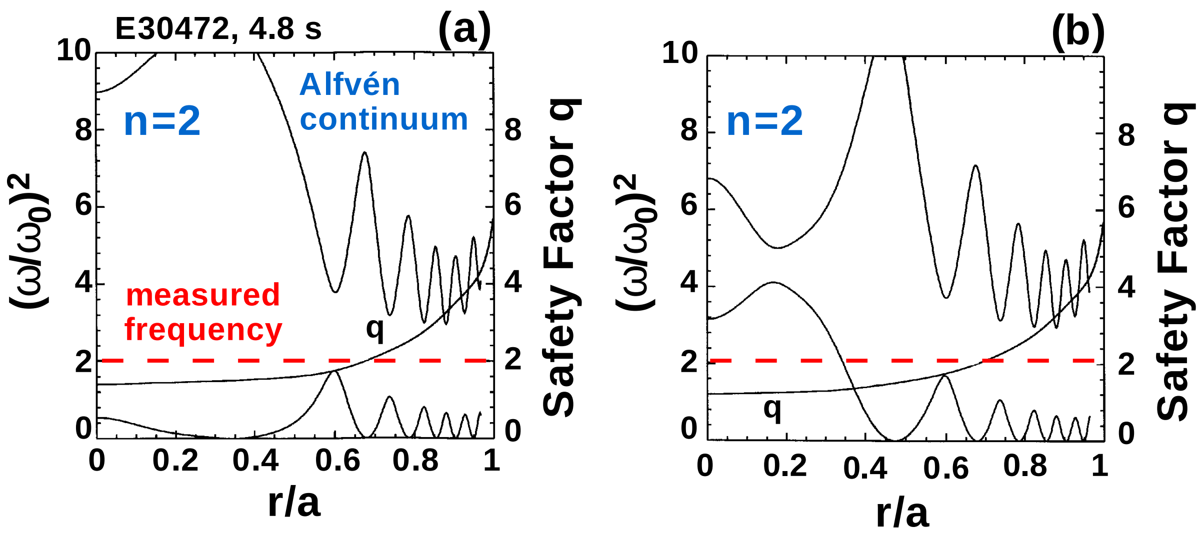

FIG. 4. (a) Alfvén continuum spectrum for the n=2 mode, safety factor profile (q) and measured TAE frequency (dotted line) at 4.8 s in the discharge shown in FIG. 2. (b) Similar ones for q_0=1.2 assumed.

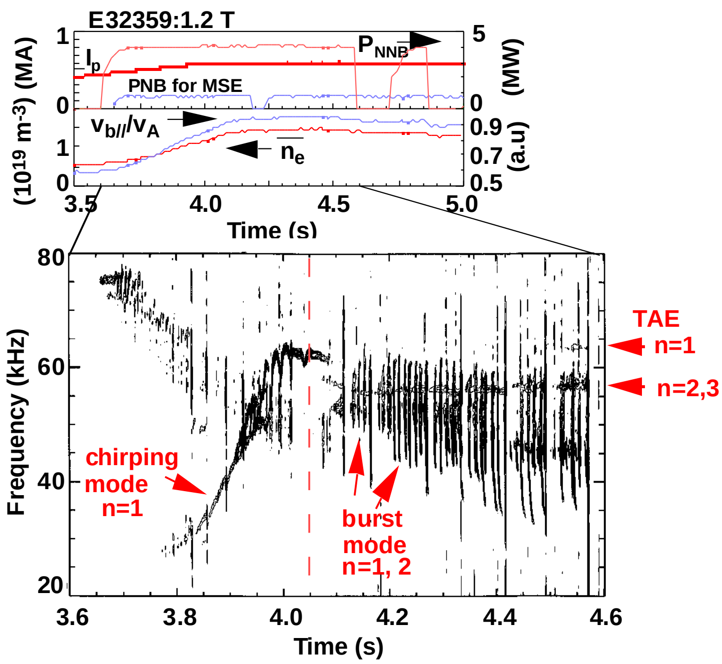

FIG. 5. Top; Time traces of plasma current , NNB power ,beam power for MSE diagnostics, line averaged-electron density and a ratio $v_{b||}/v_A$ are shown. Bottom; Frequency spectrum of magnetic fluctuations measured during the D^0-NNB injection into a deuterium plasma. Beam energy is 360 keV and toroidal magnetic field at the center is 1.2 T. Toroidal mode numbers are shown for some typical modes.

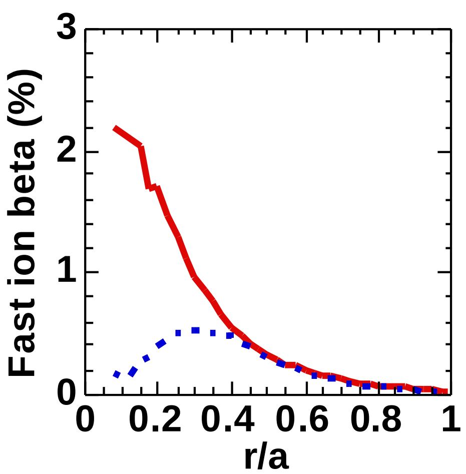

FIG. 6. Profiles of fast ion beta when only upper beam line is used (solid line) and only lower beam line is used (dotted line).

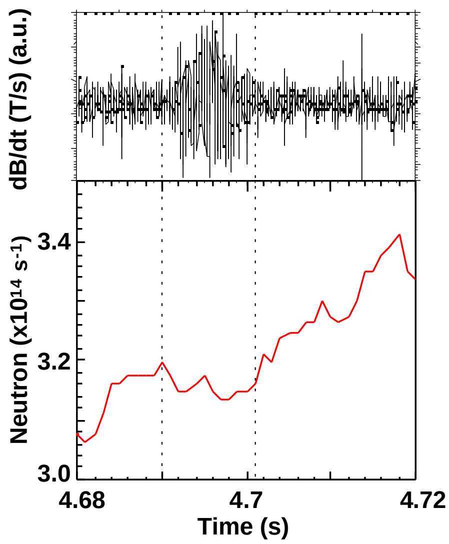

FIG. 7. Temporal behavior of magnetic fluctuation (top) and neutron emission rate (bottom) when a burst mode appears.

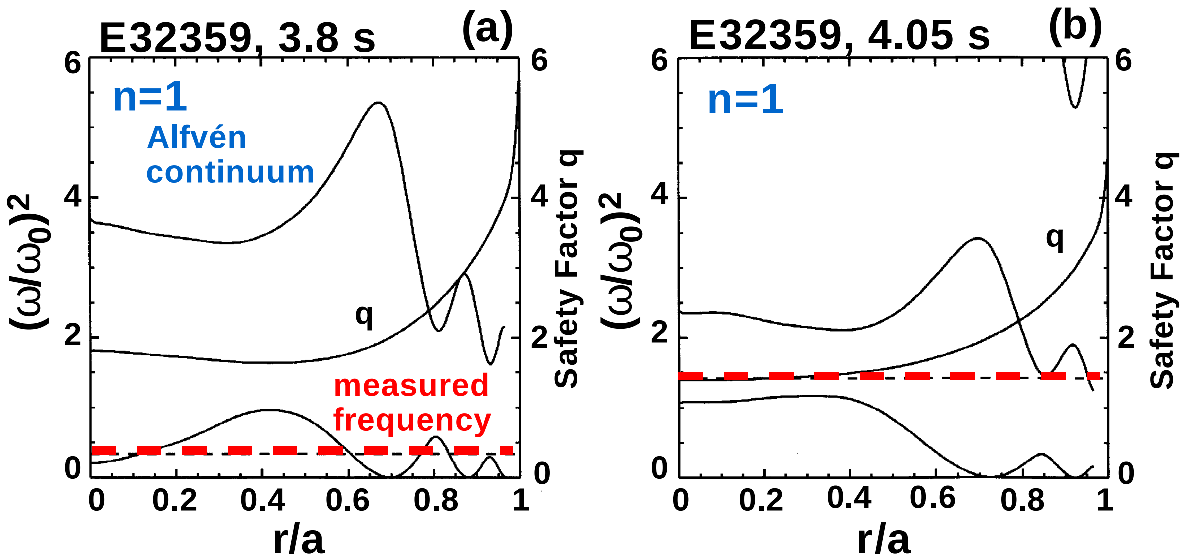

FIG. 8. Alfvén continuum for n=1 mode and profile of safety factor (q) at the start of chirp [(a), 3.8 s] and at the end of chirp [(b), 4.05 s] in the discharge shown in FIG. 5. Chirping mode frequency is shown with dotted line in each figure.

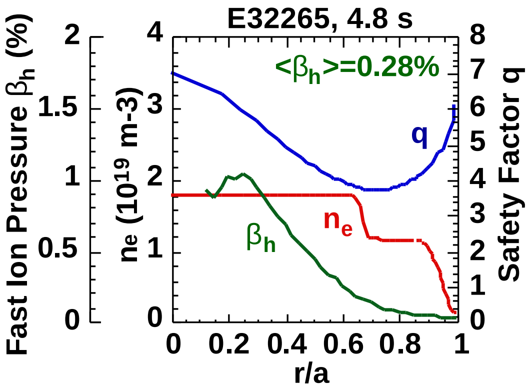

FIG. 9. Profiles of safety factor (q) , electron density (n_e) and hot ion beta (β_h) in a strongly-reversed shear plasma without exciting AEs by NNB injection. Volume-averaged hot ion beta $<\beta_h>$ is shown in figure.

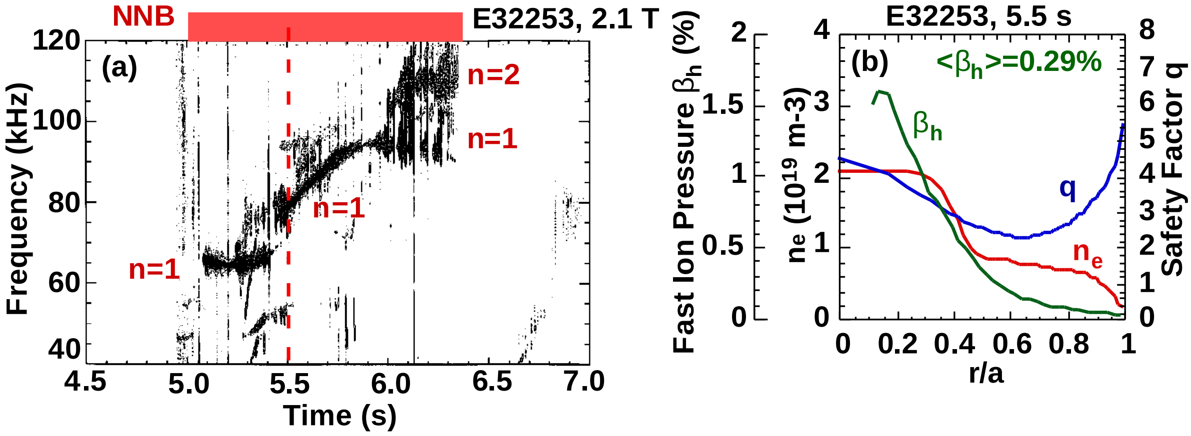

FIG. 10. (a); frequency spectrum of TAE modes observed in a reversed shear plasma. (b); profiles of safety factor (q) , electron density (n_e) and hot ion beta (β_h) at 5.5 s in figure (a),

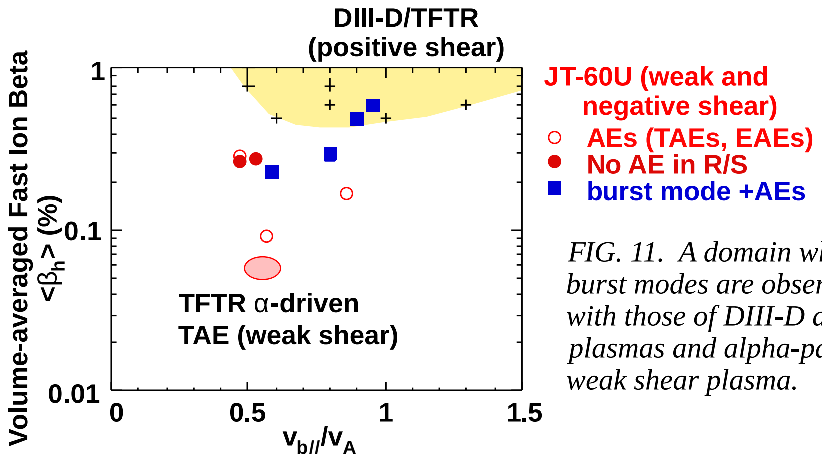

FIG. 11. A domain where Alfvén eigenmodes and burst modes are observed in JT-60U is compared with those of DIII-D and TFTR in positive shear plasmas and alpha-particle-driven TAEs in TFTR weak shear plasma.