Property of Alfven Eigenmode in JT-60U Reversed Shear and Weak Shear Discharges

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Abstract. This paper reports activity of Alfven eigenmode (AE) in the JT-60U reversed shear (RS) and weak shear (WS) plasmas. The AEs with a rapid frequency sweeping and then saturation of frequency as $q_{\min}$ decreases has been observed in low-β_h RS discharges with Negative-ion-based NBI (NNBI) or ICRH. We introduce the new type of AE which we call reversed-shear-induced Alfven Eigenmode (RSAE) near $q_{\min}$. This puzzling frequency change can be explained by considering the properties of RSAE and their transition to toroidal Alfven Eigenmodes (TAEs). We verify the existence of RSAEs and their transition to TAEs from magnetic fluctuations and measured q-profile in JT-60U plasmas. The AE amplitude is maximum during this transition, e.g., $\sim 2.4 < q_{\min} < \sim 2.7$ for the $n = 1$ mode. The recently installed diagnostic of a neutron emission profile measurement reveals the transport of energetic ions associated with MHD modes. Actually, the fast ion loss was observed by neutron profile measurement, when the $n = 1$ mode amplitude is large at this transition. It is preferable to operate outside the $q_{\min}$ transition range of $n = 1$ AE to avoid substantial fast ion loss by large amplitude AEs in RS plasmas.

1. Introduction

Magnetohydrodynamics (MHD) instabilities driven by energetic particles such as the Toroidal Alfven Eigenmode (TAE) [1] and the fishbone [2] have been extensively studied experimentally and theoretically, especially in the positive shear (PS) plasmas. These instabilities can expel energetic particles before they are thermalized with thermal plasmas, possibly leading to the quenching of fusion ignition and damage of the first wall [3]. A reversed shear (RS) plasma is potentially an efficient operation mode for steady state tokamak reactors with good confinement and a large bootstrap current fraction. The stability of TAEs in RS plasmas was first calculated by using the NOVA-K code [4] and the results indicated that TAEs in the RS configuration are more stable than those in the PS configuration [5, 6] and are more stable in the RS plasma with internal transport barrier (ITB) than that without ITB [7] because of the limited gap alignment in the shear Alfven continuum spectrum. The latter was confirmed by experimental results of AEs driven by energetic particles from ion cyclotron resonant frequency (ICRF) heating in the JT-60U plasmas [7]. The behavior of AEs in RS plasmas has not been systematically studied as those in PS plasmas. Therefore characteristics of AE in RS plasmas is not well-known, e.g., in these ICRF RS plasmas, a puzzling Alfven Eigenmode (AE) has been observed with large and rapid upward chirping in frequency, which cannot be explained by the change in frequencies of TAE type modes. In this paper we report the AE activity in the RS plasmas in JT-60U negative-ion-based neutral beam injection (NNBI) experiments and the effects of AEs on fast ion loss. We found that large and rapid frequency (both upward and downward) chirping modes exist, and these modes evolve into TAE modes as minimum of q ($q_{\min}$) decreases. We provide a theory of the reversed-shear-induced Alfven Eigenmode (RSAE) model to interpret the observed fast frequency chirping AEs. The RSAE model is also employed to explain the previously observed fast upward frequency chirping AEs observed in JT-60U ICRF RS plasma experiments. Recently, we installed six-channel neutron profile monitor to investigate the fast ion behavior. As the AEs evolve from RSAEs to TAEs, the AE amplitude is enhanced and significant fast ion loss is observed by this neutron profile measurement.

2. Property of the AE in a RS plasma

To understand the large and rapid frequency sweeping and its subsequent saturation, we propose a model of RSAE, which is the global AE near the zero shear region of the RS plasma, and its transition to TAE as $q_{\min}$ decreases. We first note that the Alfven continuous spectrums in RS plasmas are different from that in PS plasmas. Let us consider the n=1 AE in the range of $2 < q_{\min} < 3$ as an example. Figure 1 shows two shear Alfven continuous spectra, frequency vs. normalized plasma radius, in RS plasmas with (a) $q_{\min} = 2.8$ and (b) $q_{\min} = 2.3$. as examples for $2.5 < q_{\min} < 3$ and $2 < q_{\min} < 2.5$, respectively. In both cases, $n = 1$, $q(0) = 4$ at the plasma center, and $q(a) = 5$ at the plasma edge. Frequency gaps outside the region of minimum safety factor are similar in both figures. However, the gap structures around the $q_{\min}$ region are entirely different. The two gaps shown in Fig. 1(b) are two TAE gaps formed by toroidal coupling of the $m = 3$ and $m = 2$ harmonics around two $q = 2.5$ locations. On the other hand, in Fig. 1(a), there is no $q = 2.5$ and the continuum gap is formed due to the reversed shear q-profile at the zero magnetic shear location and is not induced by toroidal coupling. The lower continuum is due to the $m = 3$ harmonic and the upper continuum is due to $m = 2$. Around the upper and the lower boundary of this gap, we have found AEs with discrete eigenvalues both theoretically [9] and experimentally [10]. These modes are called Global Alfven Eigenmode (GAE) in theses papers of [9] and [10] because the resonance condition for this mode is the same as for GAE [11]. It has been generally thought that GAE except for $n = 0$ GAE is destabilized only in the plasmas with no magnetic shear like cylindrical configuration or low shear stellarator such as Wenderstein-7AS (W7-AS) [12]. Consequently TAE has been mainly remarked and investigated in many tokamaks. The damping rate caused by bulk plasmas and eigenfrequency of AEs in RS plasmas were calculated with the full wave code TASK/WM [9]. An existence of GAE was predicted and it

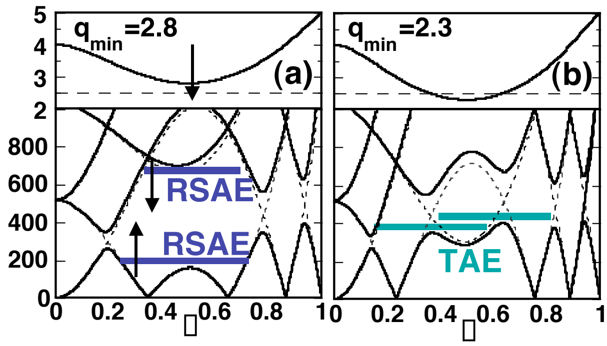

Fig. 1 Schematic drawing of the n = 1 spectrum of AEs in the RS plasma with (a) q_{min} = 2.8 and (b) q_{min} = 2.3. In both cases, n = 1, q(0) = 4 at the plasma center, and q(a) = 5 at the plasma edge.

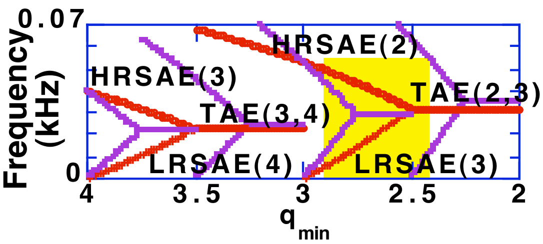

Fig. 2 The frequencies of RSAE and TAE as a function of q_{min}. The bold lines denote the frequencies of the n = 1 AEs and thin lines are for the n = 2 AEs. Numbers in the parentheses are poloidal mode numbers.

transits to TAE as q_{min} changes. From calculation of eigenfrequency GAE frequency changes as q_{min} changes. The results of the calculating damping rate indicated that TAE is more stabilized rather than GAE by bulk plasmas and is stabilized least in the transition from GAE to TAE. On the other hand, in the compact helical system (CHS) heliotron/torsatron plasmas, GAE and that TAE changed to GAE as safety factor changed were observed [10]. In contrast to W7-AS, CHS has a moderate magnetic shear comparable to that in a tokamak. Therefore TAE rather than GAE had been predicted to be destabilized in a CHS plasma and actually TAE was observed and identified. However, in CHS plasma the AEs of which frequency change cannot be explained by that of TAE were observed. However, this frequency change of AE was explained by using that of GAE. From the TASK/WM code calculation, these AE eigenfunctions are rather localized around the q_{min} location. Because GAEs original defined [11] have very different mode structure, we call these modes as RSAEs, instead of GAEs called previously.

The large and rapid frequency sweeping of AEs can be explained by RSAE and the subsequent frequency saturation by the evolution from RSAE to TAE. The AE frequencies are estimated as follows:

(1) as q_{min} decreases in the range of $(m+1/2)/n + c < q_{min} < (m+1)/n$ there are two RSAEs: the frequency of the high frequency RSAE (HRSAE) decreases as

$$f_{HRSAE} \sim (n - m/q_{min})\, v_A/2\pi R, \qquad (1)$$

and the frequency of the low frequency RSAE (LRSAE) increases as

$$f_{LRSAE} \sim ((m+1)/q_{min} - n)\, v_A/2\pi R, \qquad (2)$$

(2) for $m/n < q_{min} < (m+1/2)/n + c$, TAE gaps form and TAE frequency is approximately given by

$$f_{TAE} \sim v_A/4\pi q_{TAE} R, \qquad (3)$$

where $c \sim \Box_{min}/nR$, R is the major radius, and $q_{TAE} = (m-1/2)/n$. Note that the toroidal effect causes the m and $m+1$ harmonics to couple in the range of $m/n < q_{min} < (m+1/2)/n + c$. Thus, AEs have changed from RSAEs to TAEs in this q_{min} range. From eqs. 1-3, we show the change of RSAE frequency and its transition to the TAE by decreasing q_{min} in Fig. 2 . The bold lines denote the frequencies of the n = 1 AEs and thin lines are for n = 2. For n = 1 AEs, the HRSAE and the LRSAE merge and change to TAE when q_{min} decreases by unity. For n =

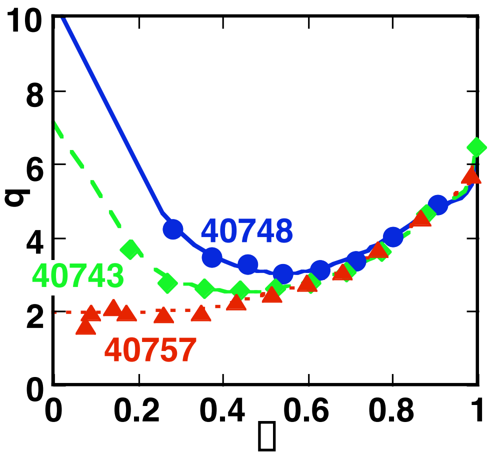

Fig. 3 The profile of safety factor when NNBI was injected.

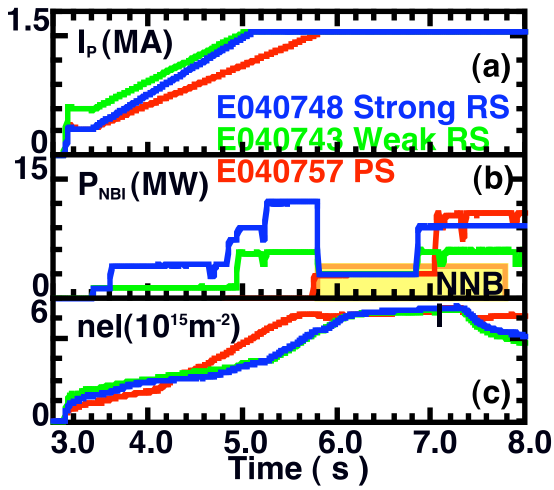

Fig. 4 Temporal evolution of plasma current (a), power of PNBI and NNBI (b), and line integral electron density (c).

2, the modes merge and change to TAE twice in the same period, and the frequency change is about two times faster than that for $n = 1$.

3. AEs in RS plasmas in JT-60U NNBI Experiments

The accurate reconstruction of q-profile is required for AE investigation. The q-profile measurement with MSE including the reconstruction of magnetic surface has recently been greatly improved. Moreover, the q-profile measurement is more accurate with higher magnetic field. Therefore, the experiments for AEs destabilized by NNB in JT-60U RS plasmas were carried out with a relatively high 3.73 T toroidal field (B_t) and 1.3 MA plasma current (I_p). Furthermore, for RSAE study, the position of q_{min} is formed at the more outer region of plasma as possible and the value of q_{min} is reduced to below 3. To investigate the effect of q-profiles on AE stability, the q-profile is changed during NNBI (Fig. 3) by changing the ramp-up rate of plasma current and the injected power of positive neutral beams (PNB) as shown in Fig. 4. The beta value of energetic particles is relatively low at β_h ~0.1 - 0.2 %, which is, however, comparable to that expected for ITER. We measured the AE frequency and amplitude and determined the toroidal mode number n by Mirnov coils with a 500~kHz sampling rate.

In the E40739 shot the hydrogen NNB of E_{NNBI} ~360 keV energy and P_{NNBI} ~ 4 MW power was injected into hydrogen RS plasmas from $t = 5.8$ s to $t = 7.2$ s. The ratio of the beam velocity parallel to toroidal magnetic field to the central Alfven velocity is $V_{b//}/V_A(0) \sim 0.5$. q in the region of $r/a < 0.65$ decreased gradually as shown in Fig. 5. Also, q_{min} decreased steadily from ~3.0 to ~2.45 in the period from 5.8 s to 7.0 s as shown in Fig. 6(a). Magnetic fluctuations with large frequency sweeping in the AE frequency range were observed (shown in Fig. 6(c)). Because β_h is relatively low (β_h ~ 0.12 %), only the $n = 1$ AE is observed. AEs with $n > 1$ are barely observed and they can be excited if β_h increases. An $n = 1$ AE frequency sweeps up from 40 to 90 kHz over the period t = 6.0-6.5 s. Another $n = 1$ mode appears to be sweeping down in frequency from 130 to 90 kHz in the same period. The large upward/downward frequency sweeping from t = 6.0 - 6.5 s cannot be explained by the change of V_A because the electron density

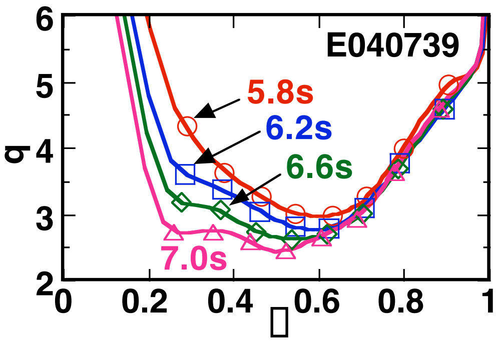

FIG. 5 Temporal evolution of the q-profille measured with MSE.

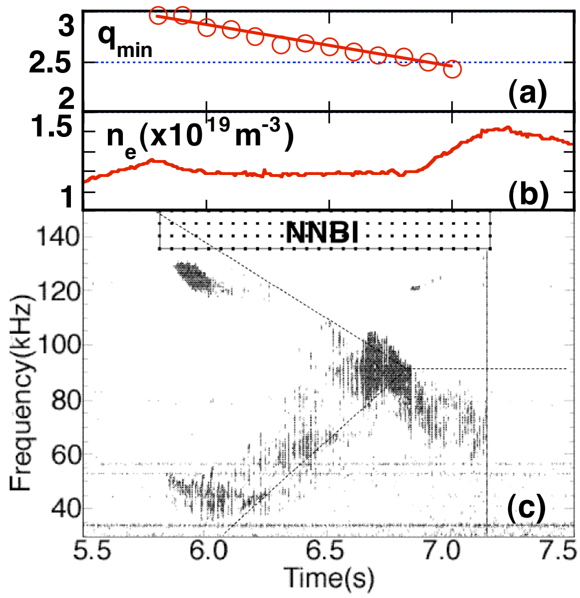

FIG. 6 Temporal evolution of qmin (a), line averaged electron density (b), a typical behavior of frequency spectrum of the n = 1 AE (c). Broken lines denote estimated frequency from the RSAE model normalized by observed frequency at q = 2.5

changed only less than 5 %. In the period t = 6.5 - 6.8 s the n = 1 AE frequency saturates. After t ~ 6.8 s the n = 1 AE frequency decreases due to the increase of electron density. The model of RSAE and its transition to TAE can explain the observed upward and downward frequency sweeping and subsequent frequency saturation shown in Fig. 6(c), where the broken lines denote the estimated model frequency calculated with eqs. 1-3 and normalized by the observed frequency at t = 6.8 s (q = 2.5). The hatched area in Fig. 2 is corresponding to observed AE frequency in Fig. 6(c).

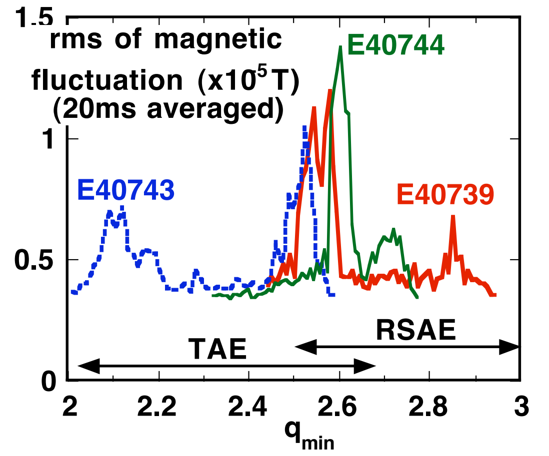

FIG. 7 Dependence of AE magnetic fluctuation amplitude on qmin. The n = 1 AE amplitude is enhanced in the range of ~2.4 < q_{min} < ~2.7.

The observed AE amplitude are enhanced during t ~ 6.65 - 6.85 s in Fig. 6(c) when the AE frequency is saturated. To investigate the dependence of mode amplitude on the q-profile change, we show the mode amplitude versus q_{min} for three shots in Fig. 7. When NNBI was injected, the values of q_{min} are about 3.0, 2.8 and 2.6 for the shots of E40739, E40744 and E40743, respectively. For all these cases the n = 1 mode amplitude is largest in the range ~2.4 < q_{min} < ~2.7, which is independent of the time length after NNB injection. This experimental result is consistent with results of calculation with TASK/WM.

We present a possible reason why AE amplitude is enhanced in the transition from LRSAE to TAE. Let us again consider the n=1 AE in the range of 2 < q_{min} < 3. For ~2.7 < q_{min} < 3 the lower frequency LRSAE is close to the adjacent Alfven continuum and suffers large continuum damping (Fig. 8(a)). For 2.5 < q_{min} < ~2.7 the toroidal coupling effect of the m = 2 and m = 3 harmonics modifies the RSAE gap to TAE gap. The mode is a mixture of TAE and RSAE and will suffer weaker continuum damping (Fig. 8(b)). For q_{min} < 2.5 RSAE no longer exists because the RSAE gap has closed up at q_{min} = 2.5 and two TAE gaps open up. TAE at the inner gap is usually destabilized due to large pressure gradient of energetic particles. However, it also encounters continuum damping at the outer TAE gap location because the

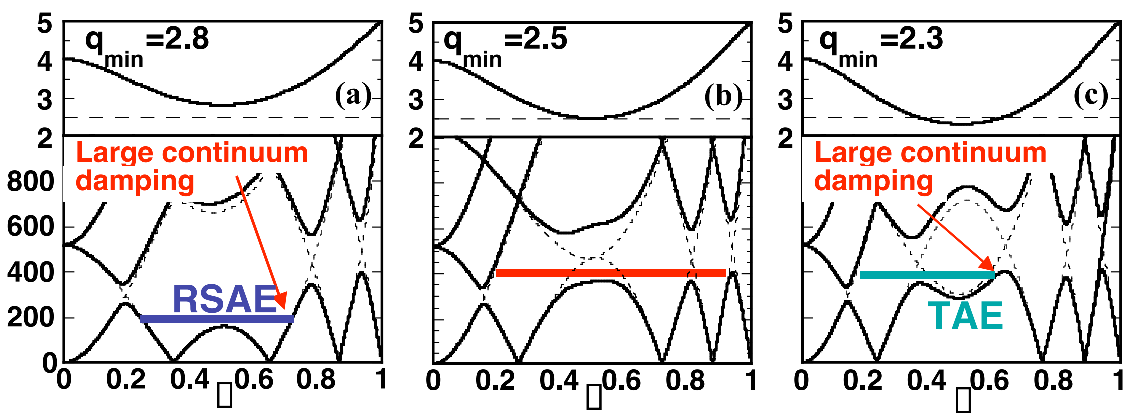

Fig. 8 Schematic drawing of the n = 1 spectrum of AEs (bottom) with q-profile (upper) in the RS plasma for RSAE phase of q_{min} = 2:8 (a), transition phase of q_{min} = 2:5 (b), and TAE phase of q_{min} = 2:3 (c). In both cases, n = 1, q(0) = 4 at the plasma center, and q(a) = 5 at the plasma edge. In the case of RSAE and TAE phase AEs suffer large continuum damping.

density at the inner TAE gap is larger than that at the outer gap (Fig. 8(c)). From these considerations, we expect the continuum damping rate of AEs to be smallest in the ~2.4 < q_{min} < ~2.7 range, which was confirmed by the TASK/WM code calculation [9]. Thus, to avoid large amplitude AEs in RS plasmas, it is preferable to operate outside the q_{min} transition range for n = 1.

4. RSAE in RS Plasmas in JT-60U ICRF Experiments

The RSAE model has also been applied to understand AEs with large and rapid upward frequency chirping in previous JT-60U ICRF RS plasma experiments [7,8]. As shown in Fig. 9(a) the frequencies of n ~2-11 modes observed from 6.0 s to 6.6 s increase ~100 - 300 % in a short period of ~200 ms. The large and rapid change in the mode frequency cannot be explained by a temporal change in plasma density and toroidal flow. The line averaged electron density decreases only ~ 4 % during 6.2 to 6.6s. Moreover, from the profile of the toroidal rotation velocity measured from the charge exchange recombination spectroscopy the Doppler-shift frequency is less than n kHz for the toroidal mode number n. Furthermore, these modes have the following features: (1) the n = 1 mode was not detected; (2) frequencies of higher n AEs increase more rapidly; (3) the higher n AEs are detected more frequently; and (4) there is a period in which no modes are detected (t ~6.65 - 6.75 s). From t = 6 to 7.5 s qmin decreases from ~ 2.4 to ~ 1.7, and we plot the frequencies of n = 1 - 9 LRSAE and TAE versus q_{min} in Fig. 9(b), which is calculated by eqs. 1-3, agrees well with the observation shown in Fig. 9(a). The n = 1 RSAE cannot be detected because it is predicted that the RSAE suffers large continuum damping due to its low frequency. From the RSAE model the frequency sweeping rate of RSAEs with a toroidal mode number n is n times faster than that with n = 1, which is consistent with the observed faster increase in frequency for higher n mode. Also, because they emerge n times during the period q_{min} decreases by unity, higher-n RSAE should be observed n times more frequently. The 1.95 < q_{min} < 2.05 range in Fig. 9(b) is filled with n>9 AEs, which are not observed from 6.65s to 6.75 s in Fig. 9(a).

5. Fast ion transport induced by AE

NNB-AE experiments are performed in JT-60U deuterium RS plasmas with relatively high β_h

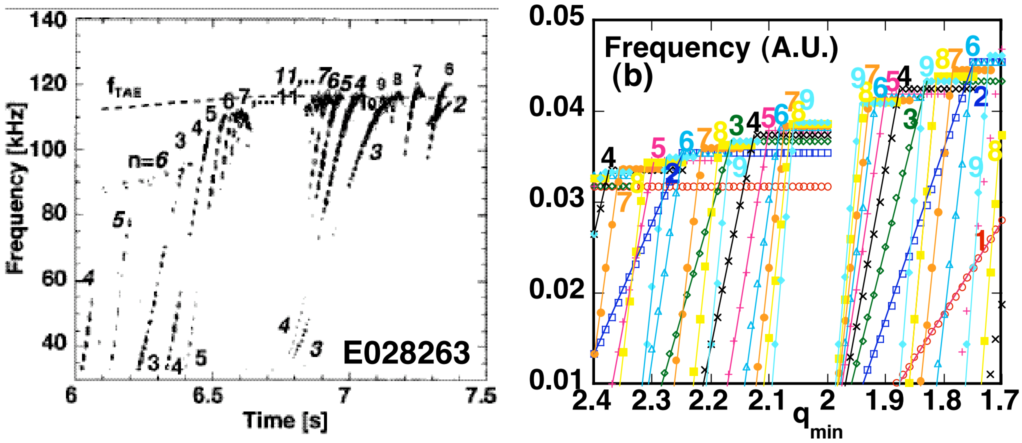

FIG. 9 Typical temporal evolution of AE frequency changes observed in a JT-60U ICRF heated RS plasma [8] (left), and the frequencies of n = 1 - 9 LRSAEs (solid upward-sloping lines) and TAEs (horizontal aligned marks) as a function of the qmin decrement (right).

to investigate transport of fast ions. WS deuterium discharge with $B_t \sim 1.2$ T, $V_b/V_A \sim 1$ and $\langle\beta_h\rangle \sim 0.6$ % was performed for investigation of fast ion transport induced by large bursting AE. The drop of the neutron emission rate and increase in fast neutral fluxes have been observed as the result of the enhanced radial transport of fast ions during the bursting modes (Fig. 10) [13, 14]. The increased fast neutral flux depending its energy is consistent with wave-particle resonance and loss mechanism [13]. We newly installed six channel neutron profile monitor to measure 2.45 MeV DD fusion neutron profile for investigation of fast ion behavior further [15]. On occurrence of large bursting modes, peripheral signals ($r/a \geq 0.48$) increase and center signals ($r/a \leq 0.34$) decrease, which shows the redistribution of energetic ions. It is estimated by OFMC code that the fast ion profile around $r/a \sim 0.2$ - 0.4 is steep. This suggests that fast ions in such region mainly interact with AE modes and the steeper gradient is relaxed in terms of redistribution of the fast ions to the outer plasma region of $r/a >\sim 0.4$.

In the E040739 shot there is no neutron flux data because of the hydrogen plasma. Therefore, we performed RS deuterium discharge with a smaller B_t of 2.1 T or study of fast ion transport with MSE q-profile measurement. In this discharge, we observed $n = 2$ and $n = 3$ AEs in addition to the $n = 1$ AE because of relatively higher $\beta_h \sim 0.4$ %. We observed suppression of the total neutron count, when the $n = 1$ RSAE and AE in the transition from RSAE to TAE were destabilized as shown Fig. 11. After $n = 1$ AE disappeared after t ~ 5.7 s, the total neutron count recovered about 20 % even though $n = 2$ and $n = 3$ AEs still remained. This suppression of neutron count is considered due to fast ion loss because the neutron profile monitor suggested that neutron emission is suppressed in all over the plasma region and electron density and ion temperature did not changed from $t = 5.8$ s to 6.2 s. Difference in transport of fast ions seems to be explained by the difference of eigenfunctions of AEs in the WS experiment and in the RS experiment. For the previous WS case, the eigenfunction seems to be localized in the central plasma region, namely such as core localized mode, because of low magnetic shear there. On contrary this, for the RS case, RSAE exists around $r/a \sim 0.5$. Therefore, AEs can transport fast ions outer region in the RS plasmas than in the WS plasma.

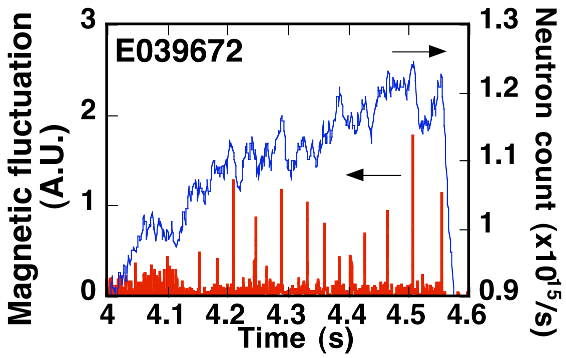

FIG. 10 Temporal evolution of neutron yieldings and magnetic fluctuation of AEs during large bursting modes were observed.

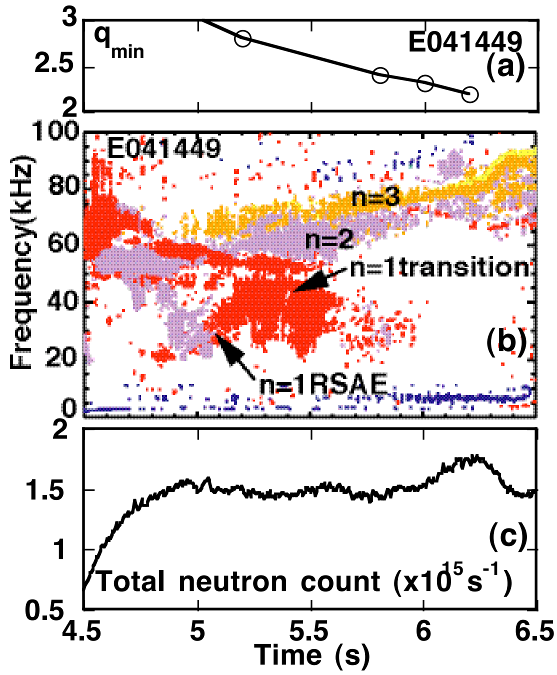

FIG. 11 Temporal evolution of qmin (a), a typical behavior of frequency spectrum of AEs (b), total neutron count rate (c).

6. Conclusions

We performed NNB-AE experiment in JT-60U RS plasma with accurate q-profile measurement to investigate the property of AEs in RS plasmas. The n = 1 NNB-AEs with a rapid frequency sweeping and then saturation of frequency as $q_{\min}$ decreases were observed in these plasmas. We introduced the RSAE model to explain such AEs with a rapid frequency sweeping observed in RS plasmas. The frequency sweeping AEs and sequent the saturation of frequency can be explained by RSAEs and the transition from RSAE to TAE. The previously observed rapid frequency sweeping of ICRF-AE with n > 1 in JT-60U RS plasmas can also be well explained by the RSAE model. The AE amplitude is maximum during this transition, e.g., ~2.4 < $q_{\min}$ < ~2.7 for the n=1 mode. On the other hand, we newly installed six channel neutron profile monitor to measure 2.45 MeV DD fusion neutron profile for investigation of fast ion behavior. By using this neutron profile detector, we observed the restribution of fast ions in WS deuterium discharge with B_t~ 1.2 T and β_h~ 0.6 %, when large bursting AEs were destabilized. As opposed to this, substantial fast ion loss was observed in RS deuterium discharge with B_t~ 2.1 T and β_h~ 0.4 %, when the n = 1 mode amplitude is large at transition from RSAE to TAE. Difference in transport of fast ions seems to be explained by the difference of location of eigenfunctions of AEs in WS and RS plasmas. From RSAE model RSAEs with n transit to TAE n times when $q_{\min}$ decrease by unity. Therefore, the n = 1 RSAE transits to TAE only once. It is preferable to operate RS plasmas outside of the $q_{\min}$ transition range for n = 1, e.g., ~2.4 < $q_{\min}$ < ~2.7 AE to avoid substantial fast ion loss due to large amplitude AEs.

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References

[1] CHENG C. Z. and CHANCE M. S. , Phys. Fluids **29** (1986) 3695.
[2] MCGUIRE K. et al., Phys. Rev. Lett. **50** (1983) 891.
[3] I. P. B. Editors, Nucl. Fusion **39** (1999) 2471.
[4] CHENG C. Z. , Phys. Reports **211** (1992) 1.
[5] OZEKI T. et al., Nucl. Fusion **35** (1995) 1553.
[6] OZEKI T. et al., Plasma Phys. Controlled Fusion, A371 (1997) **39**.
[7] KIMURA H. et al., in Fusion Energy 1996 (Proc. 16th Int, Conf. Montreal, 1996), IAEA, Vienna, 1997, vol. 3, p.295.
[8] KUSAMA K. et al., Nucl. Fusion **38** (1998) 1215.
[9] FUKUYAMA A. et al., in 6TH IAEA Technical Committee Meeting on Energetic Particles in Magnetic Confinement Systems, 12-14, October, 1999, Naka (IAEA, Vienna, 1999).
[10] TAKECHI M. et al., in 2nd IAEA Technical Committee Meeting on Steady-State Operation of Magnetic Fusion Devices, 25 29 October 1999, Fukuoka (IAEA, Vienna, 1999).
[11] APPERT K. , GRUBER R. , TROYON F. , and VACLAVIK J. , Plasma Phys. **24** (1982) 1147.
[12] WELLER A. *et al.*, Phys. Rev. Lett. **72** (1994) 1220.
[13] SHINOHARA K. et al., Nucl. Fusion **42** (2002) 942.
[14] TOBITA K. et al., Fusion Science and Technol. **42** (2002) 315.
[15] ISHIKAWA M. et al., submitted to Review of Scientific Instrument (2002)