# Energetic Ion Transport by Alfvén Eigenmodes Induced by Negative-Ion-Based Neutral Beam Injection in the JT-60U Reversed Shear and Weak Shear Plasmas

M. Ishikawa , M. Takechi, K. Shinohara, Y. Kusama, C. Z. Cheng1), G. Matsunaga, Y. Todo2) , N. N. Gorelenkov1), G. J. Kramer1), R. Nazikian1), A. Fukuyama3) and the JT-60 team

Japan Atomic Energy Research Institute, Naka-machi 319-0193, Japan
1) Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ 08543, USA
2) National Institute for Fusion Science, Toki 509-5292, Japan
3) Department of Nuclear Engineering, Kyoto University, Kyoto 606-8501, Japan.

E-mail: ishikawm@fusion.naka.jaeri.go.jp

**Abstract.** To investigate energetic ion transport induced by Alfvén eigenmodes (AEs) the neutron emission profile measurement and the charge exchange (CX) neutral particle flux measurement by Natural Diamond Detector has been performed simultaneously in the JT-60U for the first time. It was found from the CX neutral particle flux and spectrum measurements that energetic neutral particles in a large energy range (100 - 370 keV) were enhanced due to Abrupt Large-amplitude Events (ALEs) of TAEs in weak shear plasmas. The neutron radial profile was redistributed due to ALEs. The energetic ion profiles inferred from these measurements indicate that ALEs cause a radial redistribution of energetic ions of a large energy range from the core region to the outer region of the plasma in weak shear plasmas. This energy range is consistent with the resonance condition between the mode and the energetic ions. In reversed shear plasmas, reversed-shear-induced AEs (RSAEs) and their transition to TAEs as the minimum value of the safety factor decreases has been observed. Neutron measurements suggest energetic ion loss is large in the transition phase from RSAEs to TAEs.

## 1. Introduction

In burning plasmas with a high $\alpha$-particle pressure gradient, Alfvén eigenmodes (AEs) such as the toroidicity-induced AE (TAE) [1] can be destabilized by $\alpha$-particles. The destabilized AEs can induce enhanced transport of $\alpha$-particles from the core region, which can cause the degradation of the performance of a fusion reactor. Lost $\alpha$-particles may also damage the first wall. Thus, the understanding of alpha particle transport due to unstable AEs is important. AEs have been extensively studied and several kinds of AEs have been predicted theoretically and observed in toroidal confinement devices experimentally. Furthermore, effects of AEs on energetic ions have been studied in TFTR[2], DIII-D[3], and JT-60U[4, 5] and so on. So far, however, it has not been reported in details how energetic ions behave in plasmas and how energetic ions are lost.

In JT-60U, the ITER relevant parameter regime of $0.1\% < \beta_h < 1\%$ and $v_{b//}/v_A \sim 1$ has been studied recently with the Negative-ion-based Neutral Beam (N-NB) Injection in order to assess the AE activity and the effect of AEs on the loss of energetic ions [6]. In weak magnetic shear (WS) plasmas, bursting modes called Fast Frequency Sweeping (FS) mode and Abrupt Large-amplitude Event (ALE) in the frequency range of TAEs have been observed during N-NB injection. In particular, ALEs are found to cause large energetic ion transports. Moreover, in JT-60U reversed magnetic shear (RS) plasmas the reversed-shear-induced AEs (RSAEs) and their transition to TAEs as the minimum value of the safety factor ($q_{min}$) decreases have been observed [7]. In order to investigate the energetic ion transport due to these AEs induced by N-NB energetic ions, the neutron emission profile measurement [8] and the charge-exchange (CX) neutral particle flux and spectrum measurement by newly installed natural diamond detector (NDD) [9] were performed in JT-60U for the first time. The neutron emission profile measurement is of great importance for the knowledge of the ion temperature profile or alpha particle emission in future fusion devices such as ITER [10], and can also be used for plasma transport study. Since neutrons are dominantly produced via beam-target ion fusion reaction in N-NB injected plasmas, a change of the neutron emission profile indicates a change of the energetic ion density profile. Thus, the neutron emission profile measurement is a useful tool for the study of energetic ion transport.

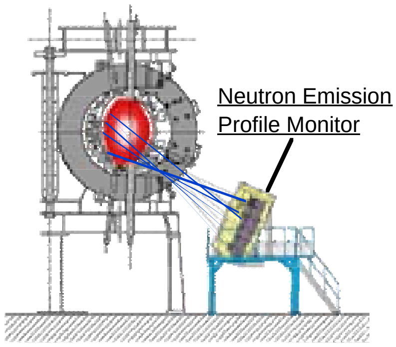


*Fig.1 Illustration of the JT-60U neutron emission profile monitor and its collimation geometry. The line-of -sight chords show the viewing poloidal cross section of the plasma.*

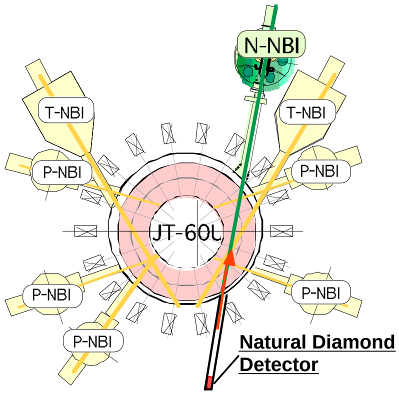


*Fig.2 Illustration of the JT-60U CX-NPA. Natural diamond detector used as a neutral pariticle spectrometer.*

The CX neutral particle measurement (spectrometer) is also one of the most effective diagnostics to investigate energetic ion behavior because CX neutral particles provide information such as energy distribution function of confined energetic ions.

In this paper we present the results of the neutron emission profile measurement and CX neutral particle flux measurement during AEs and the associated energetic ion transport inferred from these measurements in JT-60U.

## 2. Diagnostics for investigation of energetic ion transport

In order to investigate energetic ion behavior we measured two kinds of neutron emission rate and CX neutral particle flux and energy spectrum. One neutron emission rate is the total neutron emission rate by Fission Chamber [11] and the other is the neutron emission profile measured by the neutron emission profile monitor [8]. The neutron emission profile monitor consists of a fan-shaped 6-channel collimator array (2.6m x 1.5m x 1.3m) viewing a poloidal cross section, and is located about 5 m away from the plasma center as shown in Fig. 1. The CX neutral particle flux and spectrum are measured by the natural diamond detector (NDD) [9]. The NDD detects the neutral particles whose pitch angles are almost same as that of the birth energetic ions by the N-NB as shown in Fig. 2. The energetic ions are neutralized through a charge exchange reaction with the neutral particles $D^0$ or the hydrogen-like carbon ions $C^{5+}$ and are emitted from the plasma as neutral particle fluxes. We also measured the AE frequency, amplitude and mode number by Mirnov coils located near the first wall.

## 3. Energetic ion transport due to bursting AEs in Weak Shear plasmas.

We performed AE experiments using N-NB in weak shear (WS) plasmas with the following parameters: $I_P = 0.6$MA, $B_T = 1.2$T, $P_{NNB} = 5$MW, where $P_{NNB}$ is the power of N-NB. Furthermore, two units of positive-ion-based NB were also injected for the diagnostics of ion temperature and q-profile. In this discharge, the ratio of the beam ion velocity parallel to the magnetic field to the Alfvén velocity was $v_{b//}/v_A = 1.03$, and the volume averaged hot ion beta was $\langle\beta_h\rangle \sim 0.6$ %. The parameter domain for energetic ions produced by N-NB in this experiment is similar to the domain of α-particles in ITER.

Figure 3 shows the waveforms of plasma parameters during N-NB injection. Figure 3(a) shows the time traces of plasma current and injected N-NB power. Figures 3(b) and (c) show the time traces of the frequency spectrum and mode amplitude with frequency of 20 - 80 kHz, respectively. At t = 4.6 s, $n_e(0) \sim 2.2 \times 10^{19} m^{-3}$, $T_e(0) \sim 1.8$ keV, $T_i(0) \sim 1.9$ keV, q(0) = 1.4 and $Z_{eff} \sim 2.1$, where $n_e(0)$, $T_e(0)$, $T_i(0)$ and q(0) are electron density, electron temperature, ion temperature and safety factor at the plasma center and $Z_{eff}$ is the effective charge, respectively. Bursting TAEs called fast frequency-sweeping (FS) modes and abrupt large-amplitude events (ALEs) are observed as shown in Fig. 3(b) and (c). Fast FS modes have a

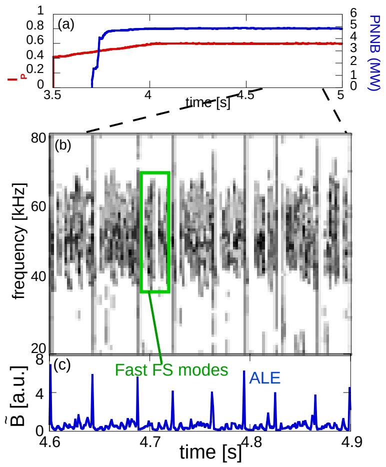


*Fig.3 Time traces of plasma parameters of E43014. (a): Plasma current, $I_P$, and N-NB injection power. The beam energy of N-NB is 397keV. (b) Frequency spectrum of magnetic fluctuations. (c) Amplitude of magnetic fluctuations with frequency of 20-80 kHz.*

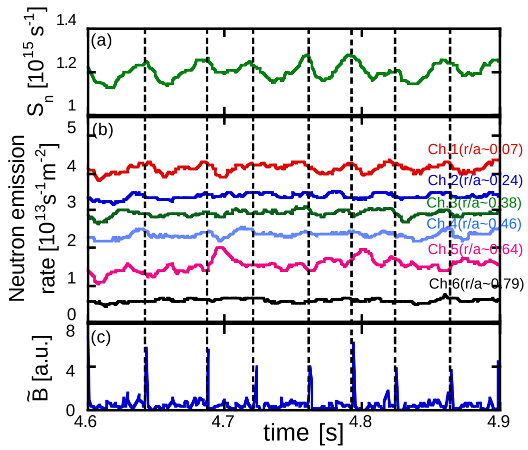


*Fig.4 Neutron signals during the occurrence of ALEs in the E43014 shot. (a) Total neutron emission measured by Fission chamber. (b) Signals of the neutron emission profile monitor. The innermost channel is shown on top. (c) Amplitude of magnetic fluctuations.*

time scale of 1-5 ms and its frequency chirps toward both the upper and lower sides. On the other hand, ALEs have a time scale of 200-400 μs and their amplitudes are large with $\delta B/B \sim 10^{-4}$ near the first wall. The occurrence of ALEs coincides with large drop of neutron flux and indicates fast ion transport. Therefore, we determine the energetic ion transport by measuring the neutron emission profile and the CX neutral flux and spectrum during ALEs.

The time trace of the neutron emission rate during N-NB injection is shown in Fig. 4 together with the magnetic fluctuation amplitude. Figure 4(a) shows the time trace of the total neutron emission rate. Figure 4(b) shows the time trace of the neutron emission rate of each channel measured by the neutron emission profile monitor with the innermost channel at the top. The magnetic fluctuation amplitude shown in Fig. 4(c) is the same as in Fig. 3(c). During ALEs the total neutron emission rate is either increased or reduced slightly, but after ALEs the total neutron emission rate reduced significantly over a time period of 10 to 20 msec as shown in Fig. 4(a). As shown in Fig. 4(b), the neutron emission signals from the central region (r/a < 0.38) reduced, while signals from the peripheral region (r/a > 0.64) increased after ALEs. This suggests the energetic ion profile is redistributed due to ALEs.

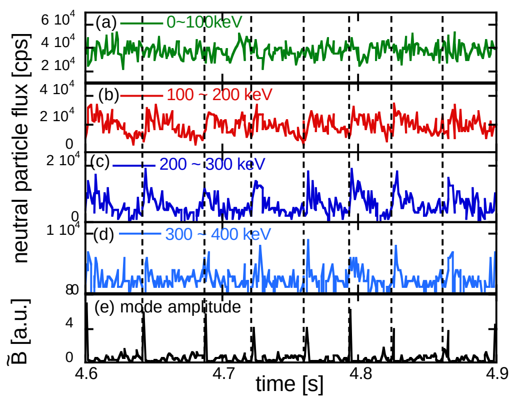


*Fig.5 Time trace of neutral particle fluxes with energy windows of (a) 0 – 100 keV, (b) 100 – 200 keV, (c) 200 – 300 keV, (d) 300 – 400 keV and (e) mode amplitude during N-NB injection in the E43014 shot.*

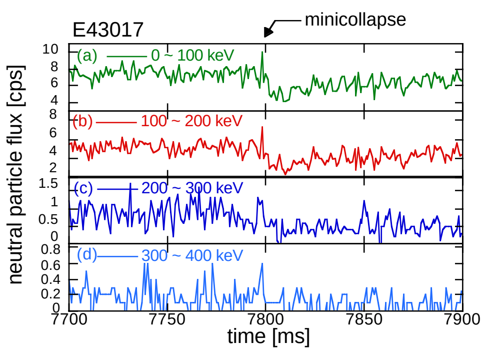


*Fig.6 Time trace of neutral particle flux with energy windows of (a) 0 – 100 keV, (b) 100 – 200 keV, (c) 200 – 300 keV, (d) 300 – 400 keV during N-NB injection in the E43017 shot.*

Figure 5 shows the time trace of mode amplitude and neutral particle flux with energy

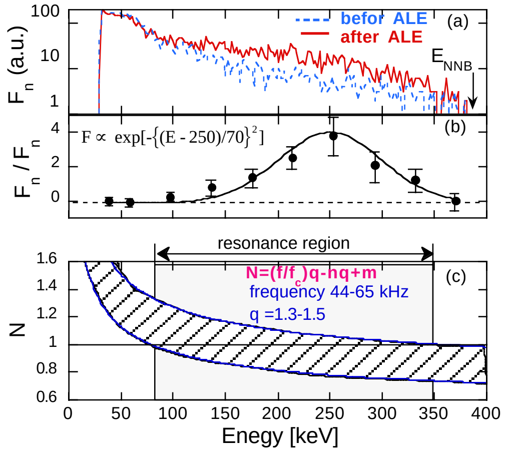


*Fig.7 Energy spectrum of (a) neutral particle fluxes before and after ALE, (b) the fraction of enhanced neutral particle fluxes by ALEs and (c) a diagram of the resonant condition under the experimental condition of E43014. The resonance energy region is 70 ~ 350 keV.*

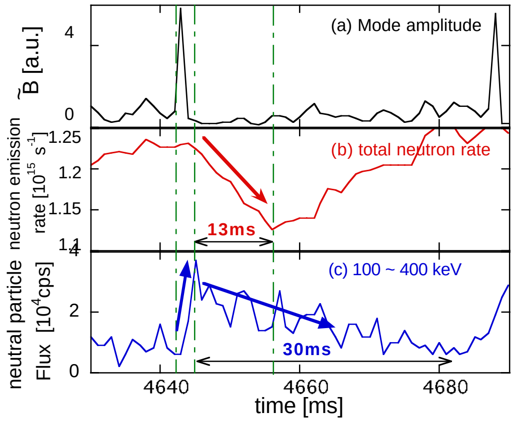


*Fig.8 Time trace of (a) magnetic fluctuations, (b) total neutron emission rate, and (c) neutral particle fluxes with energy of 100 ~ 400 keV in the E43014 shot.*

windows of (a) 0 – 100 keV, (b) 100 – 200 keV, (c) 200 – 300 keV, and (d) 300 – 400 keV during N-NB injection, respectively. The enhancement of neutral particle flux with energy of 100 – 400 keV can be clearly observed during ALE. On the other hand, neutral particle flux with energy of 0 – 100 keV is not enhanced. In contrast with this, Fig. 6 shows the time trace of the neutral particle flux in the same energy windows as shown in Fig. 5 for the E43017 shot. The enhancement of neutral particle flux is observed in all energy windows due to a mini-collapse in the neutral particle flux was observed. These results indicate ALEs cause transport of energetic ion in a large energy range. Figure 7(a) shows the energy distribution of the neutral particle flux before ALE and after the neutral particle flux enhancement due to ALE is observed, and Fig. 7(b) shows the fraction of enhanced neutral particle flux due to ALE. One sees that the neutral particle flux in the energy range of 100 - 370 keV is enhanced due to ALEs in the E43014 shot. This result suggests that the emitted neutral particles satisfy the resonance condition with the mode, expressed by $N = (f/f_c)q\text{-}nq\text{+}m$ [12], where N is an integer, f is the mode frequency, $f_c$ is the toroidal transit frequency of energetic ions, n is the toroidal mode number, m is the poloidal mode number and q is the safety factor. A diagram of the resonant condition is shown in Fig. 7(c) for the experimental condition of the E43014 shot. The shadow area shows the broadness of the resonant condition, which arises from the broadness of mode frequency as shown in Fig. 3(b) and the ambiguity in the q profile. Thus, it is estimated that the resonant energy range is 80 ~ 350 keV for N = 1. The energy range of enhanced neutral particle flux corresponds qualitatively to the resonant energy range for N = 1. This result suggests that the enhanced neutral particle fluxes result from the resonant interaction between energetic ions and AE modes.

Indeed the time evolutions of the neutron signals indicate a rather complex set of time scales as shown in Fig. 4. However, the neutral particle flux measurement indicates the behavior of energetic ions. Figure 8 shows expanded time traces of (a) mode amplitude, (b) total neutron emission rate and (c) neutral particle flux with energy of 100 - 400 keV. The energetic neutral particle flux increases rapidly during an ALE burst and decreases slowly after the ALE burst. This could indicate that during ALE bursts energetic ions resonating with bursting ALEs are transported to the larger radial domain. The slower decay in the neutron emission rate over a 10 to 20 msec period is due to lower target background plasma density at larger r/a, slowing-down and redistribution of these transported energetic ions. Also, the small increases of neutral particle flux during slowing down over 30 msec after ALE bursts suggest some further energetic ion transport due to much smaller amplitude fluctuations such as Fast FSs that occur between ALE bursts as shown in Fig. 3(b). The neutron emission rate starts to increase after decreasing for 10 to 20 msec by the supply of N-NB injection.

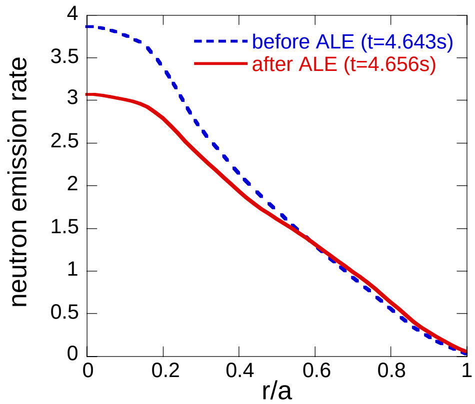


*Fig.9 Radial neutron emission profiles obtained by the Abel inversion before ALE at t = 4.643 s and after ALE at t = 4.656 s in the E43014 shot.*

Since the beam-target neutrons account for over 90% of the total neutron emission according to the calculation by TOPICS code [13] and the energy range of enhanced neutral particles is over 100 keV, the observed change in the neutron emission profile is attributed to the transport of energetic ions produced by N-NB. Thus, Figures 4 and 5 indicate that ALEs redistribute energetic ions from the core region to the outer region of the plasma.

To understand how ALEs cause energetic ion transport, we estimate the change of energetic ion density profile from the neutron emission profiles. Here, we choose a representative time slice at t = 4.643 s (before ALE ) and at t = 4.656 s (after the ALE). However, because the values shown in Fig. 4(b) are the line-integrated neutron emission rate along each line of sight, we have to employ the Abel inversion method to obtain the radial neutron emission profile. We use the Abel inversion by Wiener Filter method in JT-60U [14]. The neutron emission profiles obtained by the Abel inversion at t = 4.643 s and 4.656 s are shown in Fig. 9.

To infer the transport of energetic ions from the change in the neutron emission profile, we assume for simplicity that the fusion reaction is only due to beam-target ions. As mentioned above, the beam-target ion reaction accounts for over 90% of the total neutron emission rate in such N-NB injection experiments from the TOPICS code calculation. Therefore, the fusion reactivity

$$\langle \sigma v \rangle = \iint dv_1 dv_2\, f(v_1) f(v_2) \sigma(v') v' \qquad v' = v_1 - v_2$$

can be well approximated by the beam-target reactivity. The beam-target reactivity for a mono-energetic beam of speed $v_b$ reacting with Maxwellian target ions with thermal speed $v_{th}$ [15] is given by

$$\langle \sigma v \rangle_{bt} = \frac{1}{v_b v_{th} \sqrt{p}} \int \sigma v^2 \left[ \exp\left( -\left( \frac{v - v_b}{v_{th}} \right)^2 \right) - \exp\left( -\left( \frac{v + v_b}{v_{th}} \right)^2 \right) \right] dv \cdot \tag{1}$$

The total reactivity is obtained by averaging $\langle \sigma v \rangle_{bt}$ over the beam energy distribution. For the fusion cross section σ in Eq. (1), we employ the equation presented by Bosh et al. [16]. Therefore, the neutron emission rate $S_n$ is given by

$$S_n = n_{th} n_b \cdot (\sigma v)_{bt}, \tag{2}$$

where $n_{th}$ and $n_b$ are the density of target plasma and beam ions, respectively, $(\sigma v)_{bt}$ is the averaged $\langle \sigma v \rangle_{bt}$ over the beam energy distribution. We need to provide the energy distribution function of beam ions, and we use the energy distribution function calculated by OFMC code [17]. $S_n$ is obtained from Fig. 9 and $n_{th}$ is obtained from the measured data. Furthermore, $(\sigma v)_{bt}$ is estimated by the above calculation. To obtain the energetic ion density $n_b$ spatial profile, we divide the normalized minor radius into 51 intervals and calculate $n_b$ in each interval. We then compare t he $n_b$ profiles before and after the

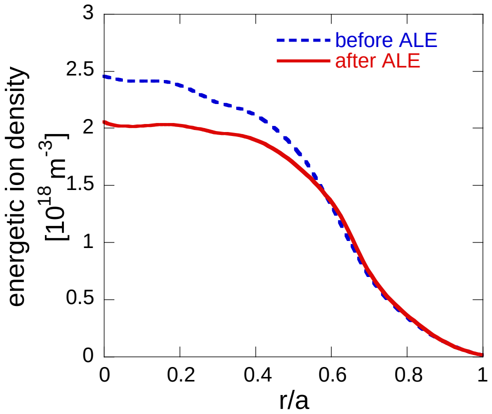


*Fig.10 energetic ion density profiles before ALE at t = 4.643 sec and after ALE at t = 4.656 sec in the E43104 shot. They are estimated from the neutron emission profile measurement.*

occurrence of ALEs.

Before the occurrence of ALEs, the energetic ion density profile can be calculated by Eq. (3). On the other hand, it is necessary to take into account the result of CX neutral particle flux measurement to obtain the energetic ion density after ALEs. The energetic ion density after ALEs, $n_{after}$, is derived as follows. We express the energy dependence of enhanced neutral particle fluxes due to ALEs shown in Fig. 7(b) by a fitting function F(E) given by

$$\mathrm{F(E)} \propto \exp\left[-\{(\mathrm{E}-250)/70\}^2\right]$$

where $\int_{\mathrm{E_{MIN}}}^{\mathrm{E_{MAX}}} \mathrm{F(E)\,dE} = 1$ and E is energy in keV. $E_{MAX}$ and $E_{MIN}$ are the maximum energy and the minimum energy of the enhanced energy range, respectively. $E_{MAX}$ = 370 keV and $E_{MIN}$ = 100 keV in this case. We assume that the energetic ion density $N_{TR}$ with energy distribution function F is transported just in the radial direction due to ALEs. Then, the energetic ion density after ALEs, $n_{after}$ is given by,

$$n_{after} = n_{before} + \mathrm{N}_{TR} \tag{3}$$

Also, $S_{after}$ is expressed by

$$S_{after} = S_{before} + N_{TR} n_{th} \left\{ \langle \sigma v \rangle_{bt}' \Big|_{E_{reso.MIN}}^{E_{reso.MAX}} \right\}$$

$$\therefore N_{TR} = \frac{S_{after} - S_{before}}{n_{th} \left\{ \langle \sigma v \rangle_{bt}' \Big|_{E_{reso.MIN}}^{E_{reso.MAX}} \right\}}$$

where $\langle \sigma v \rangle_{bt}' \Big|_{E_{reso.MIN}}^{E_{reso.MAX}}$ is the average fusion reactivity with energy distribution F(E) over the energy region of $E_1$ to $E_2$. $n_{after}$ is estimated by substituting $N_{TR}$ to Eq. (3).

Figure 10 shows the energetic ion density profiles before and after the ALE estimated from Eqs. (2) and (3), respectively. One can see that the center region of energetic ion profile is reduced but the outer region increases slightly. The inversion radius of these profiles is r/a ~ 0.58. The total energetic ion population integrated over the volume is reduced by 4% by the ALE, with a 16% reduction in the central region of r/a < 0.58.

Thus, the energetic ion density profile inferred from the neuron emission profile measurement and the CX neutral particle flux measurement indicates that ALEs induce both radial redistribution and loss of energetic ions in the resonant energy range.

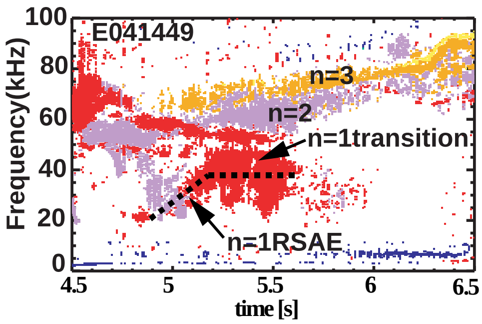


*Fig.11 Time trace of AE frequency spectrum in RS plasmas (E41449).*

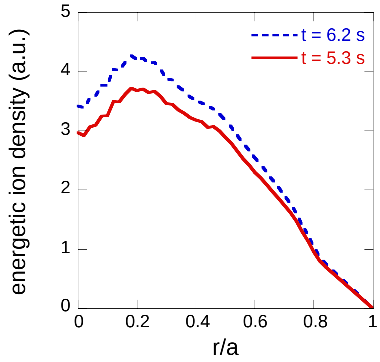


*Fig.12 Energetic ion density profiles during mode transition phase (from RSAE to TAE) at t = 5.3 s and after n=1 mode disappears at t = 6.2 s in the E41449 shot. The fast ion density profiles are estimated from*

## 4. Energetic ion transport due to AEs in Reversed Shear plasmas

We have observed another kind of AEs in RS plasmas [7]. Figure 11 shows the time trace of spectrum of magnetic fluctuation in N-NB injected RS plasma (E41449, $B_T$ = 2.1T, $I_P$ = 0.9 MA). We observed not only n = 1 mode but also n = 2, 3 modes. For the n = 1 mode, after frequency sweep upward, saturation of frequency is observed. This time evolution of the n = 1 mode can be explained by the reversed shear-induced Alfven eigenmode (RSAE) model [7, 18, 19]. The RSAE model predicts that as the minimum value of safety factor ($q_{min}$) decreases to 2.5, the n =1 mode changes from RSAE to TAE. RSAE is an AE localized near the $q_{min}$. The RSAE model also predicts that the mode amplitude is enhanced in the mode transition phase. In this discharge, the neutron emission profile measurement was performed during AEs in RS plasmas for the first time. Figure 12 shows the energetic ion profile inferred from the neutron emission profile measurement at (a) the transition phase from RSAE to TAE (at t = 5.3 s) and (b) after the n = 1 mode disappears (at t = 6.2 s). The energetic ion profile is significantly reduced due to the n = 1 mode at t = 5.3s. The total energetic ion population integrated over the volume is reduced by 11.4% during the transition from RSAE to TAE. However, since n = 2, 3 modes exist in this plasma even after the n = 1 mode disappears, the effect of these modes on energetic ion transport needs to be investigated.

## 5. Summary

In the present work the neutron emission profile measurements and neutral particle flux measurements are performed investigate the transport of energetic ions due to AE induced by N-NB energetic ions in JT-60U. It was found from the neutral particle flux and spectrum measurements that energetic neutral particle fluxes in a large energy range (100 - 370 keV) are enhanced due to ALEs. Neutron emission profile measurements suggest that the neutron radial profile is redistributed due to ALEs. The energetic ion density profile is inferred from these measurements, and the result indicates that ALEs cause a radial redistribution of energetic ions with a large energy range from the core region to the outer region of the plasma in weak shear plasmas. This energy range of the transported energetic ions is consistent with the resonance condition between the mode and the energetic ions. This suggests that the energetic ion transport results from resonant interaction between energetic ions and TAEs. In reversed shear plasmas, the reversed-shear-induced AEs (RSAEs) and their transition to TAEs have been observed. The neutron emission profile measurements were performed for the first time and suggest that the energetic ion transport is large as RSAEs transit to TAEs and over 10% of the total energetic ion population integrated over the volume is reduced in this phase.

**Acknowledgment**

The authors would like to thank member of JAERI for their support and useful discussions. This work was partly supported by JSPS, Grant-in-Aid for Scientific Research (B) No.14208056. Work done by PPPL group is supported by US DOE contract No. DE-AC02-CHO-3073.

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