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Confinement Degradation of Energetic Ions due to Alfvén Eigenmodes in JT-60U Negative-Ion-Based Neutral Beam Injection Plasmas

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Abstract.

Confinement degradation of energetic ions due to Alfvén Eigenmodes (AEs) induced by negative-ion-based neutral beam injection for the classical confinement is quantitatively evaluated for the first time. AEs, whose frequency largely sweep with the time scale of a few hundreds millisecond and then saturate as the minimum value of the safety factor decrease, have been observed in JT-60U. These mode behavior can be explained by reversed-shear induced AEs (RSAEs) and the transition from RSAEs to TAEs. Measured total neutron emission rate (Sn) in the presence of these AEs is compared with that predicted by a classical theory. As a result, confinement degradation of energetic ions is confirmed, especially, it is largest in the transition phase from RSAEs to TAEs, where the maximum reduction rate for the classical confinement is estimated as $(\Delta Sn/Sn)_{max} \sim 45$ %. Line-integrated neutron emission profile is also compared with that predicted when assuming that the confinement is classical. The result indicates energetic ions are transported from core region of the plasma due to these AEs. Further, changes in energy distribution of charge exchange neutral fluxes suggest radial transport is due to the resonance interaction between energetic ions and AEs.

1. Introduction

Alpha particles play an important role in the plasma heating in burning plasmas. However, a high alpha particle pressure gradient can induce Magnetohydrodynamics (MHD) instabilities such as Alfvén Eigenmodes (AEs) (toroidicity-induced AEs (TAEs) [1, 2]) or Energetic particle modes (EPMs) [3]. These MHD instabilities can cause enhanced transport of alpha particles from the core region of the plasma, which degrade the performance of burning plasmas. Moreover, lost alpha particles may also damage the first walls. Thus, the understanding of alpha particle transport due to these instabilities is an urgent research issue for ITER. Then, several kinds of AEs and EPMs have been predicted theoretically and observed experimentally and their effects on energetic ions have been studied. Recently, another type of AEs, whose frequency largely sweep with the time scale of a few hundreds millisecond and then saturate as the minimum value of the safety factor (q_{min}) decreases, have been extensively studied in reversed shear (RS) plasmas of JT-60U [4], JET [5], DIII-D [6], TFTR [7], Alcator C-MOD [8] and CHS [9, 10] and in weak shear (WS) plasmas of JET [11] and JT-60U [12]. These frequency behavior can be explained by reversed-shear induced AEs (RSAEs) [13] or Alfvén Cascades (ACs) [14] and its transition to TAEs. In the previous studies in JT-60U, it has been reported that the transition phase was most unstable. Thus, mechanism of excitation of such AEs becomes to be understood. However, the effect of these AEs on confinement of energetic ions has not been understood yet.

In present work, we have investigated the effect of RSAEs and its transition to TAEs on energetic ions. RSAEs and TAEs are excited by injecting negative-ion-based neutral beam (NNB) into WS plasmas. In order to evaluate the confinement degradation of energetic ions in the presence of RSAEs and TAEs, the total neutron emission rate is compared with the calculated one by a classical theory using the Orbit Following Monte-Carlo (OFMC) code [15]. Further the energetic ion transport due to these modes is investigated using the neutron emission profile measurement [16] and the charge exchange (CX) neutral particle flux measurement [17]. Section 2 describes plasma parameters of AE experiments and diagnostics for the investigation of the energetic ion transport. The property of observed AEs with the large frequency sweeping with the time scale of a few hundreds millisecond and then frequency saturation in WS plasmas is described in Section 3. The associated evolution of energetic ion confinement degradation from the OFMC code calculation is given in Section 4. Section 5 presents the results of the neutron emission profile measurement and the CX neutral particle flux measurement for energetic ion transport studies. The summary is presented in Section 6.

2. JT-60U experiment

We performed AE experiments using NNB in WS plasmas with the following parameters: the plasma current $I_P = 0.8 \sim 1.0$ MA, the toroidal magnetic filed $B_T = 1.5 \sim 1.7$ T, $P_{NNB} = 3.5 \sim 4.9$ MW and $E_{NNB} = 370 \sim 390$ keV, where P_{NNB} and E_{NNB} are the power and energy of NNB, respectively. $v_{b//} / v_A \sim 0.8 \sim 1.0$ and the classical calculation with the OFMC code showed $\langle\beta_h\rangle = 0.4 \sim 0.6$ %, where $v_{b//} / v_A$ is the ratio of the NNB ion velocity parallel to the magnetic field to the Aflvén velocity and $\langle\beta_h\rangle$ is the volume averaged energetic ion beta by NNB injection. The slowing down time of energetic ions is also calculated using the classical OFMC code to be ~ 500 ms. Several units of positive-ion-based neutral beam (PNB) are also injected to measure radial profiles of the ion temperature (T_i) and the safety factor (q) and to control the radial profile of q, and the energy of PNBs are ~ 80 keV, respectively.

In order to investigate energetic ion behavior, we measure the total neutron emission rate (Sn) and the radial profile of the neutron emission rate. Because the beam-thermal reaction neutron rate, $Sn_{b\text{-}th}$,

$$Sn_{b\text{-}th} \propto \int n_b n_i \langle\sigma v\rangle \, dv,$$

accounts for ~ 90 % of the total neutron emission rate in such AE experiments, changes in the neutron emission rate directly mean change in the energetic ion population and/or the energetic ion velocity distribution if the bulk plasma parameters don't change. Here, n_b and n_i are the densities of beam ions and bulk ions, respectively, and $\langle\sigma v\rangle$ is the fusion reactivity of beam-thermal reaction. Especially, the radial profile of neutron emission rate provides information on the radial profile of energetic ions, Therefore, a measurement of the radial profile of neutron emission rate is a useful tool for transport studies of energetic ions. Sn is measured by a Fission Chamber [18]. The radial profile of the neutron emission rate is measured using a large neutron collimator array [16]. The number of channel of the collimator array is 6. The covered area is lower half of the poloidal cross section of the plasma and the viewing extent of each collimator channel at the center of the torus is about 200 mm. Those sampling rate is 10 ms. CX neutral particle fluxes and energy spectrum are also measured to investigate energetic ion behavior [17]. Because CX neutral particles emitted from the plasma have information of the velocity distribution of confined energetic ions. The CX neutral particle fluxes and spectrum are measured by a natural diamond detector (NDD) [19, 20]. The NDD detects neutral particles whose pitch angles are almost the same as that of birth energetic ions produced by the NNB injection. The sampling rate of the CX neutral particle measurement is 2 ms. Further, frequency, amplitude and mode number of AEs are measured by Mirnov coils located near the first wall.

3. Characteristic of Instabilities with a Rapid and Large Frequency Sweep.

Figure 1 shows time trace of (a) q_{min}, (b) the frequency spectrum and (c) the mode amplitude with frequency of 100 – 160 kHz, respectively, in the NNB injected weak reversed shear plasma (E43978, B_T = 1.7 T, I_P = 1.0 MA, P_{NNB} = 4.0 MW, E_{NNB} = 370 keV). As q_{min} decreased from ~ 2.0 to ~ 1.5, the n = 1 instabilities with frequency of about 100 kHz appear and frequency sweeps up to about 150 kHz. Then, after q_{min} decreased below 1.5, the frequency saturates. After that, these instabilities were almost stabilized. The frequency behavior cannot be explained by change in the electron density. Then, in order to understand the large frequency sweeping with the time scale of a few hundreds millisecond and its subsequent saturation of the n = 1 instabilities in WS plasmas, we apply the model of RSAEs and its transition to TAEs as q_{min} decreases [13]. Here, the RSAEs are global AEs localized near the zero magnetic shear region of the RS plasma.

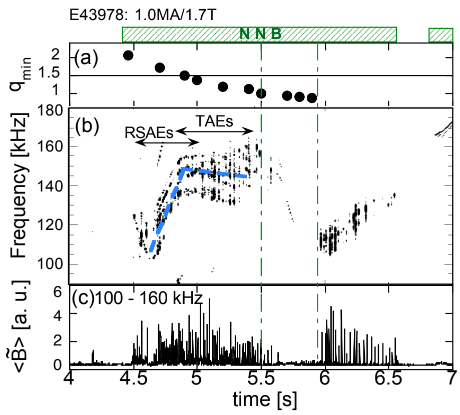

FIG. 1. Time traces of (a) q_{min} (b) Frequency spectrum of magnetic fluctuations in the range of 100 - 160 kHz and (c) amplitude of magnetic fluctuations of the n = 1 instabilities. Dotted lines in (b) denote frequency estimated using the RSAE model [13].

Shown in FIG. 2 are the Alfvén continuum spectrum for the n = 1 mode and q versus the minor radius (r/a) at (a) t = 4.7 s, (b) 5.3 s and (c) 5.7 s in the discharge shown in FIG. 1. q_{min} in FIG. 2 (a) - (c) are ~ 1.7, ~ 1.4 and ~ 1.2, respectively. According to the RSAE model in the case of this discharge, for 2 > q_{min} > 1.5, lower frequency RSAE is excited just above the lower continuum around the zero magnetic shear region shown in FIG. 2 (a). Note that another RSAE could be exited just below the upper continuum around the zero magnetic shear region. However, since AE with higher frequency are harder to be destabilized, it was not excited in this discharge. Further, for 1.5 > q_{min} > 1, TAE gap is formed around q = 1.5 surface, and then TAE is excited in the gap as shown in FIG. 2 (b). On the other hand, although there is a TAE gap in the case of FIG. 2 (c), no AEs are observed. This is considered to be due to small pressure gradient of energetic ions around the TAE gap (r/a ~ 0.5). As above, AE frequency can be estimated using the RSAE model. Broken lines in FIG. 1 (b) denote estimated frequency of n = 1 AEs with the RSAE model. As shown in FIG. 1 (b), the estimated frequency reproduces the observed frequency behavior. Thus the large frequency sweeping with the time scale of a few hundreds millisecond and its subsequent saturation of the n = 1 instabilities in the WS plasma can be explained by the RSAE model.

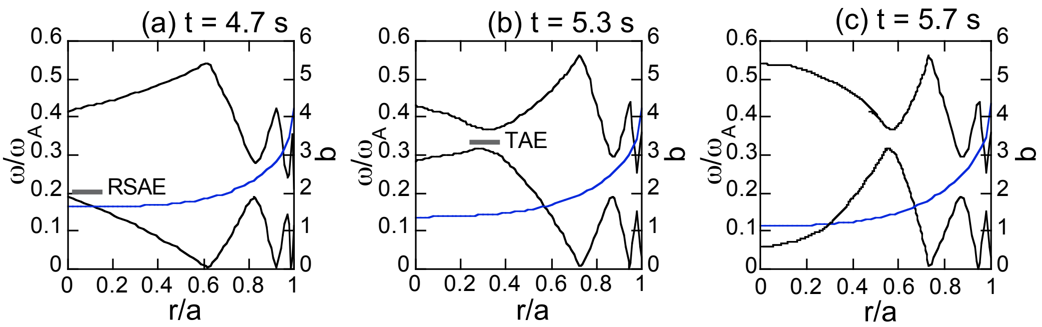

FIG. 2. Alfvén continuum spectrum for the n = 1mode and the safety factor profile at (a) 4.7s, (b) 5.3s and (c) 5.7s.

4. Confinement Degradation of Energetic Ions due to Alfvén Eigenmodes induced by NNBI

Shown in FIG. 3 (a) is the frequency spectrum of magnetic fluctuation, which is same of FIG. 1 (b). Solid line in FIG. 3 (b) shows time trace of the total neutron emission rate (Sn). Increase of Sn was suppressed with RSAEs and TAEs. After these AEs were stabilized at t ~ 5.5 s, the rate of increase of Sn was enhanced rapidly. This suggests confinement degradation of energetic ions due to these AEs. Then, in order to evaluate how confinement of energetic ions was degraåded, Sn was calculated with the OFMC code, taking into account the changes in the bulk plasma. The calculation was performed assuming that the confinement was classical and beam-thermal neutron was dominant. Actually, beam-thermal neutron emission rate accounted for ~ 90 % of total neutron emission rate according to the calculation with a transport code TOPICS [21]. Shown in solid circles of FIG. 3 (b) is the calculated Sn by a classical theory. It is found that the measured Sn is smaller than calculated one in the presence of these AEs. Whereas, after AEs were stabilized, measured one became close to calculated one, then was consistent with that at t ~ 5.9 s. This evaluation indicates confinement of energetic ions was degraded due to these AEs.

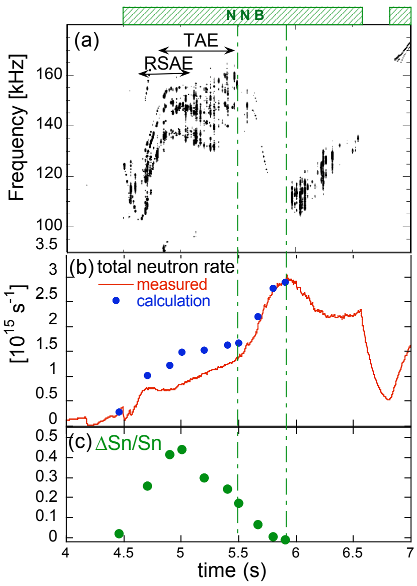

FIG. 3. Time traces of (a) the frequency spectrum of magnetic fluctuation, (b) the measured neutron emission rate (solid line) and the calculated one using the OFMC code (circles) and (c) the reduction rate of neutron emission rate (ΔSn/Sn). in E43978 shot..

Figure 3 (c) shows time trace of reduction rate of Sn, which was estimated from the ratio of measured Sn to calculated one. One can see that the rate is largest in the transition phase from RSAEs to TAEs. The previous studies that the transition phase from RSAEs to TAEs was most unstable [13] support this result. Here, the maximum reduction rate is estimated as $(\Delta Sn/Sn)_{max}$ ~ 45 % at t ~5.0s. Confinement degradation of energetic ions in the presence of RSAEs and TAEs is quantitatively evaluated for the first time.

Figure 4 (a) shows time trace of the frequency spectrum in the NNB injected weak reversed shear plasma (E45764, B_T = 1.5 T, I_P = 0.8 MA, P_{NNB} = 4.0 MW, E_{NNB} = 370 keV). Two kinds of AEs with a large frequency sweep were continuously observed in this discharge. The mode number of first AEs and second AEs is n = 1 and 2, respectively. Frequency behavior of n =1 AEs and n = 2 AEs can be explained by RSAEs and its transition to TAEs, respectively. Solid line in FIG. 4 (b) shows time trace of measured Sn. Increase of Sn was suppressed in the presence of these AEs. This indicates confinement degradation of energetic ions due to these AEs. Shown in solid circles of FIG. 4 (b) and FIG. 4 (c) are a calculated Sn by the classical theory and the reduction rate of the measured Sn from calculated one, respectively. The calculation was performed in the same way as solid circles in FIG. 3 (b) using the OFMC code. One can see that the measured Sn is smaller than calculated one in the presence of AEs. It is found, further, that reduction rate with n = 1 AEs is larger than that with n = 2 AEs. This result suggests that the effect of n = 1 AEs on confinement degradation of energetic ions is larger than that of n = 2 AEs.

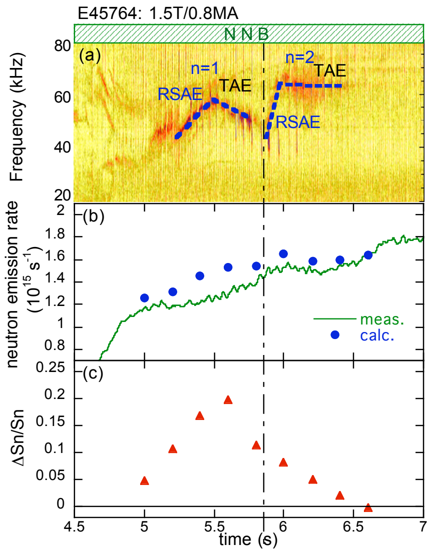

FIG. 4. Time traces of (a) the frequency spectrum of magnetic fluctuation, (b) the measured neutron emission rate (solid line) and the calculated one using the OFMC code (circles) and (c) the reduction rate of neutron emission rate (ΔSn/Sn) in E45764 shot.

5. Comparison of Slowing Down of Energetic Ions Between with and without AEs, and observation of Energetic Ion Transport

Shown in FIG. 5 is time trace of (a) the injection power of NNB and (b) the frequency spectrum of magnetic fluctuation in the range 0 ~ 100 kHz, in the NNB injected weak reversed shear (E46078, B_T = 1.7 T, I_P = 1.0 MA, P_{NNB} = 4.9 MW, E_{NNB} = 388 keV). The NNB injection was turned off from 6.5 s to 6.9 s. The n = 1 RSAEs and its transition to TAEs were observed from 5.6 s to 6.5s. While only weak AE activities were observed from 6.9 s to 7.8 s, during NNB injection (later NNB injection phase, C labeled in FIG. 5 (a)). This is considered that since the injection power of the NNB was down by ~ 1 MW compared with that in an early NNB injection phase (t = 5.6 s ~ 6.5 s, B in FIG. 5 (a)) and n =1 TAE gap lies in the peripheral region, where the pressure gradient of energetic ions is small like FIG. 2 (c), n = 1 TAEs were not exited in the later NNB injection phase (C). Solid line in FIG. 5 (c) shows the measured Sn. Though Sn continued increasing in early NNB injection phase, the rate of increase changed as the AE transited. Especially, the rate of increase in the transition phase from RSAE to TAE is smallest. On the other hand, the rate of increase decreased gradually in the later NNB injection phase (C), which seems to be caused by the slowing down on energetic ions produced by the NNB. Solid circles in FIG. 5 (c) show the calculated Sn by the classical theory using the OFMC code and (d) the reduction rate of neutron emission rate (ΔSn/Sn). It is found the time evolution of the measured Sn is consistent with that of calculated one in the later NNB injection phase (C). This means that the confinement of energetic ions is classical with only weak AEs. On the other hand, the measured Sn is smaller than calculated one in the presence of these n = 1 AEs (B). This indicates confinement degradation of energetic ions due to these AEs. Further, as shown in FIG. 5 (d), the reduction rate in the transition phase is largest.

Since the measured total neutron emission rate described in Sec. 4 is a volume-integrated value, it is unknown how energetic ions are transported in the plasma and/or lost. Then, in order to investigate energetic ion transport due to these AEs, the measurements of neutron emission profile and CX neutral particle flux were performed.

Figure 6 (a) shows time trace of the frequency spectrum of magnetic fluctuation and (b) each signal of the neutron collimator array. In the diagram in FIG. 6 (b), each signal is labeled with the minimum normalized minor radius through which the sight line passed. It is found that time evolution of inner channels (r/a < 0.32) were different from that of outer channels (r/a < 0.46). Signals of outer channels increased monotonically. While, the time evolution of inner channel changed as the phase of AEs changed as shown in dotted lines in FIG. 6 (b). Contrary to this, signals of all channels increased almost monotonically in the later NNB injection phase. Figure 7 (a) shows measured line-integrated neuron emission profile and predicted neutron emission rate along each sight line when assuming that confinement was classical (classical value). In this prediction, slowing down of NNB ions is considered. Horizontal axis in FIG. 7 means the innermost normalized radius of each sight line which passed through the plasma. Compared with both, the measured one in center region is much smaller than the classical value in the transition phase (t = 6.0 s). Shown in FIG. 7 (b) is the ratio of the measured one to the classical value. The measured neutron signals in the center region (r/a < ~ 0.5) are reduced from the classical value. While, those in peripheral region are increased. On the other hand, the measured one is close to the classical value with weak AEs (t = 7.8 s). This indicates that energetic ions were transported from core region of the plasma due to these AEs. Thus, radial transport of energetic ions is confirmed from energetic ion profile predicted by assuming the classical confinement for the first time. Further it focus attention on changes in inner channels (r/a < ~ 0.32) in the transition phase. The gradient of signal of innermost

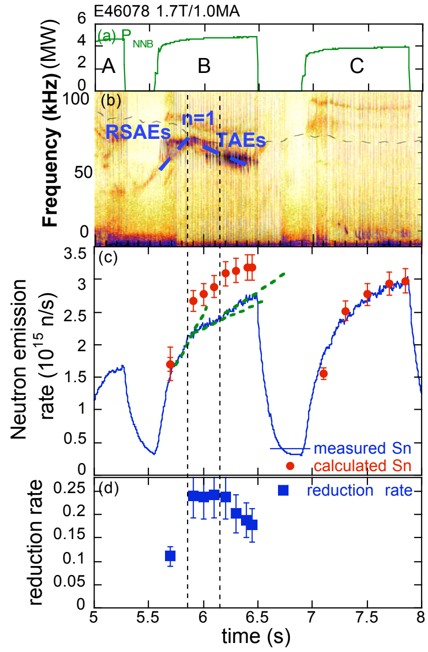

FIG. 5. Time traces of (a) the injection power of NNB, (b) the frequency spectrum of magnetic fluctuation, (c) the measured neutron emission rate (solid line) and the calculated one using the OFMC code (circles) and (d) the reduction rate of neutron emission rate (ΔSn/Sn) in E46078 shot.

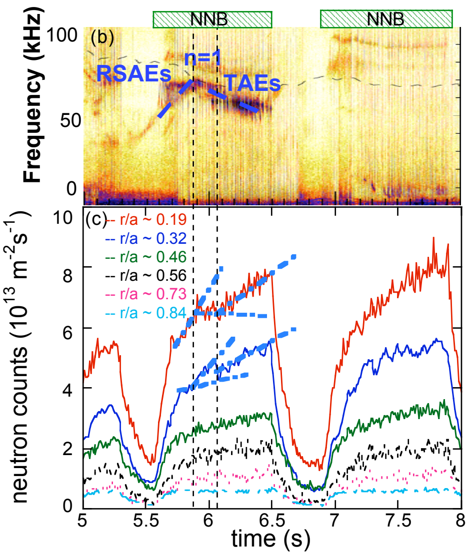

FIG. 6. Time trace of Time traces of (a) the frequency spectrum of magnetic fluctuation, and (b) signals of 6 channels neutron emission profile measurement in E46078 shot.

channel is almost zero, while signal of second channel increases as shown broken lines in FIG.6 (b). This suggests that local transport in center region is occurred in the transition phase. In this phase, AEs could appear in plasma axis because q_{min} and q = 1.5 surface both lies around at r/a < 0.3. It is considered that these AEs localized in center region of the plasma induce additional local transport of energetic ions in the center region.

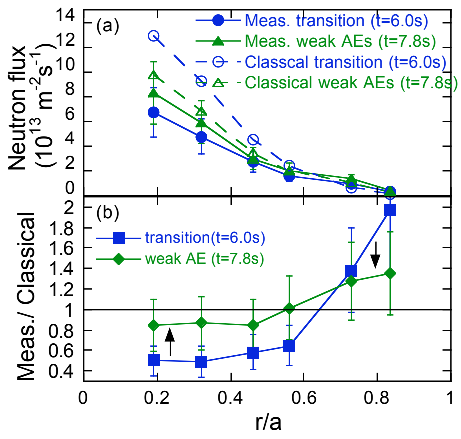

FIG. 7. (a) Line-integrated neutron signals of measurement (Meas.) in the transition phase (closed circle), w/o AEs (closed triangle) and that predicted by classical theory (Classical) in the transition phase (open circle), with weak AEs (open triangle). (b) Ratio of Meas. to Classical in transition phase (square) and with weak AEs (diamond)

Figure 8 (a) shows energy distributions of CX neutral particle flux with AEs in the transition phase (t = 5.9 ~ 6.2 s) and without AEs (t = 7.4 ~ 7.7 s). Enhancement of CX neutral particle flux with energy over 50 keV was observed. Since energetic ions are neutralized through charge exchange reactions with the neutral particles D^0 or the hydrogen-like carbon ions C^{5+} in peripheral region in the plasma and are emitted from the plasma as neutral particle, this indicate energetic ions are transported from the core region to the outer region of the plasma due to these AEs. Shown in FIG.8 (b) is the enhancement factor of neutral particle flux due to AEs. One can see that the neutral particle flux in the energy range of 50 - 300 keV is enhanced due to AEs, and the distribution of the incremental fluxes has a peak at ~ 200 keV. Here, we estimate energy of energetic ions which satisfy the resonance condition with modes and the energetic ion expressed by $N = (f/f_c)q - nq + m$ [22], where f is mode frequency, f_c is toroidal transit frequency of energetic ions, n is toroidal mode number, m is poloidal mode number and q is safety factor. Then in the transition phase, the resonance energy is estimated as 140 ~ 280 keV, where f_c = 60 ~ 70 kHz, q = 1.4 ~ 1.6, n =1, m = 2 and N = 1. These data suggest that enhance neutral particle fluxes result from the resonant interaction with AEs and energetic ions.

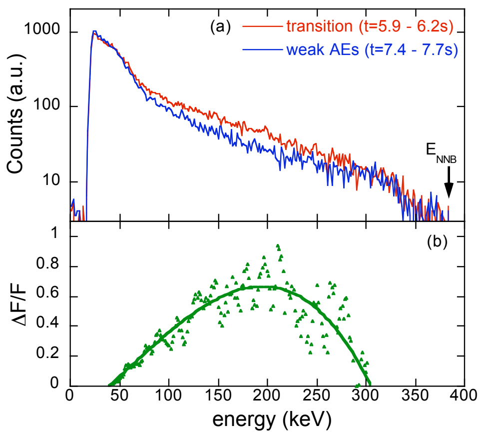

FIG. 8. Energy spectrum of (a) with the n = 1 AEs (red line) and with only weak AEs (bule line), and (b) the fraction of enhanced neutral particle fluxes by the n = 1 AEs in E46078 shot.

5. Summary

In this work, confinement degradation of energetic ions due to Alfvén Eigenmodes (AEs) induced by negative-ion-based neutral beam injection for the classical confinement is quantitatively evaluated for the first time. AEs, whose frequency largely sweep with the time sale of a few hundreds millisecond and then saturates as q_{min} decrease, have been observed in JT-60U. These mode behavior can be explained by reversed-shear induced AE (RSAE) and its transition to TAEs. Measured total neutron emission rate (Sn) in the presence of these AEs is compared with that predicted by classical theory. As a result, confinement degradation of energetic ions is confirmed, especially, it is largest in the transition phase from RSAEs to TAEs, where the maximum reduction rate for the classical confinement is estimated as $(\Delta Sn/Sn)_{max} \sim 45$ %. Line-integrated neutron emission profile is also compared with that predicted when assuming that the confinement is classical. The result indicates energetic ions are transported from core region of the plasma due to these AEs. Further change in signal of inner channels suggests local transport in center region is occurred in the transition phase. Changes in energy distribution of CX neutral fluxes also suggest that radial transport of energetic ions is induced by the resonance interaction between energetic ions and AEs.

Acknowledgments

This work was partly supported by a JSPS. Grant-in-Aid for Scientific Research (B) (No.14208056) and by a Grant-in-Aid for Scientific Researches on Priority Areas from Ministry of Education, Culture, Sports, Science and Technology (No. 17044009).

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