Observation of Confinement Degradation of Energetic Ion due to Alfvén Eigenmodes in weak shear plasmas onJT-60U

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Abstract. Confinement degradation due to Alfvén Eigenmodes has been investigated with negative ion based injection at ~ 370 keV into weak shear plasmas on JT-60U. The AEs with a rapid frequency sweeping and then saturation as the minimum value of safety factor (q_{min}) decrease have been observed. These frequency behavior can be explained by reversed-shear induced AE (RSAE) and the transition from RSAE to TAE. Reduction rate of total neutron emission rate in the presence of AEs is evaluated by calculation with Orbit Following Monte-Carlo code taking into account changing in bulk plasmas. The changes in total neutron emission rate and CX-NP flux suggested energetic ion transport due to these AEs. The evolution indicates confinement of energetic ions is degraded due to AEs. In particular, it is found confinement degradation is maximum during transition from RSAE to TAE and the maximum reduction rate $(\Delta Sn/Sn)_{MAX}$ is estimated ~ 45 %..

1. Introduction

Burning plasmas are self-sustained by alpha-particle heating. However, high alpha particle pressure gradient can destabilize Magnetohydrodynamics (MHD) instabilities such as toroidicity-induced AEs (TAEs) [1] or Energetic particle modes (EPMs) [2]. These MHD instabilities can induce enhance transport of α-particles from a core region, which degrade the performance of burning plasmas. Further lost α-particles may also damage first walls. Thus, the understanding of α-particle transport due to these instabilities is one of the urgent research issues for ITER. So far, TAEs or EPMs have been studied theoretically and experimentally. Furthermore, effects of TAEs or EPMs on energetic ions have been studied in TFTR [3], DIII-D [4], and JT-60U [5, 6] and so on. In particular, it was found that bursting modes in the frequency range of TAE, which is called Abrupt Large-amplitude Events, expelled a significant energetic ion population from core region to outer region and induce redistribution and loss of energetic ions using neutron emission profile measurements [7] and charge-exchange (CX) neutral particle flux measurement [8] in JT-60U [9].

Recently, another type AEs, which have a rapid and large frequency sweeping as the minimum values of safety factor (q_{min}) changes, are extensively studied and experimentally observed in JET [10], CHS [11, 12] and JT-60U [13] in reversed shear (RS) plasmas. AEs with a strong frequency dependence on q_{min} in reversed shear plasmas were first explained by numerical studies using the Transport Analyzing System for Tokamak/Wave Multimode (TASK/WM) code[14], which is a full code assuming that thermal particles follows their guiding center motion. Then, AEs with large frequency sweeping observed in JT-60U RS plasmas were identified as reversed-shear Alfven eigenmodes (RSAEs) [13]. On the other hand, the existence of observed large frequency sweeping modes, are called Alfvén cascades (ACs), by using the model of EPMs by Berk *et al.* [15]. However, it has not been reported how RSAEs or ACs affect energetic ions, so far.

In JT-60U weak shear (WS) plasmas, AEs with rapid frequency sweeping and then saturation of frequency as q_{min} decrease have been observed during Negative-ion-based Neutral Beam (NNB) injection [16]. The frequency evolution can be explained by RSAE and transition from RSAE to TAE. In the present work, we evaluate confinement degradation in the presence of RSAEs and TAEs in WS plasmas from the comparison between measured neutron and calculated neutron with Orbit Following Monte-Carlo (OFMC) code [17]. Further the energetic ion transport due to these modes is estimated using CX neutral particle flux measurement [8]. In this paper we present results of the experiment conducted in N-NB injected WS plasmas in order to investigate confinement degradation due to AEs. Section 2 describes diagnostics utilized to investigate energetic ion transports. The property of observed AEs in WS plasmas is described in Section 3 and the evolution of confinement degradation of energetic ions using OFMC code is given in Section 4. The summary is presented in Section 5.

2. Experimental

We performed AE experiments using N-NB in WS plasmas with the following parameters: $I_P = 1.0$ MA, $B_T = 1.7$ T, $P_{NNB} \sim 3.9$ MW, $E_{NNB} \sim 370$ keV, where P_{NNB} and E_{NNB} are the power and energy of N-NB, respectively. The slowing down time of energetic ions from NNB injection is calculated using OFMC code as ~ 500 ms. In order to measure ion temperature and safety factor, two units of positive-ion-based NB (PNB) were also injected, where both power and energy of PNBs are ~ 2.0 MW and ~ 80 keV respectively. In this discharge, $v_{b//} / v_A \sim 0.6$ and calculation with the OFMC code shows $\langle\beta_h\rangle \sim 0.4$ %, where $v_{b//} / v_A$ is the ratio of the beam ion velocity and $\langle\beta_h\rangle$ is the volume averaged classical energetic ion beta. Figure 1 shows the plasma configuration in this experiment and two NNB beam lines.

In order to investigate energetic ion behavior, we measure total neutron emission rate using Fission Chamber [18]. Because beam-thermal neutron, $Sn_{b\text{-}th}$,

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

accounts for ~ 90 % of total neutron emission rate in such AE experiments, changes in neutron emission rate mean directly those in the energetic ion population if bulk plasma parameters don't change. Here, n_b and n_i are a density of beam ions and bulk ions, respectively, and $\langle\sigma v\rangle$ is a fusion reactivity of beam-thermal reaction.The sampling late of the Fission Chamber is 1ms. The charge exchange (CX) neutral particle flux and spectrum are also measured by a NDD [9,19,20]. The NDD detects neutral particles whose pitch angles are almost the same as that of birth energetic ions produced by the NNB injection, since energetic ions are neutralized through charge exchange reactions with the neutral particles D^0 or the hydrogen-like carbon ions C^{5+} and are emitted from the plasma as neutral particles. Therefore we can investigate behavior of NNB ions. The sampling rate of the CX neutral particle measurement is 1 ms. Frequencies, amplitudes and mode numbers of the instabilities are measured by Mirnov coils located near the first wall.

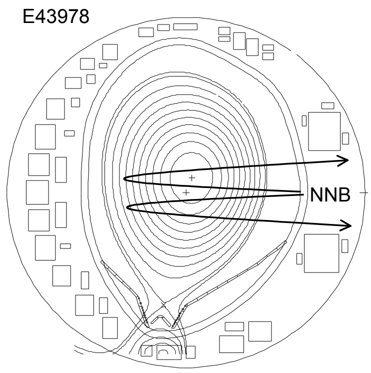

Fig.1 *plasma configuration, two beam lines of NNBs*

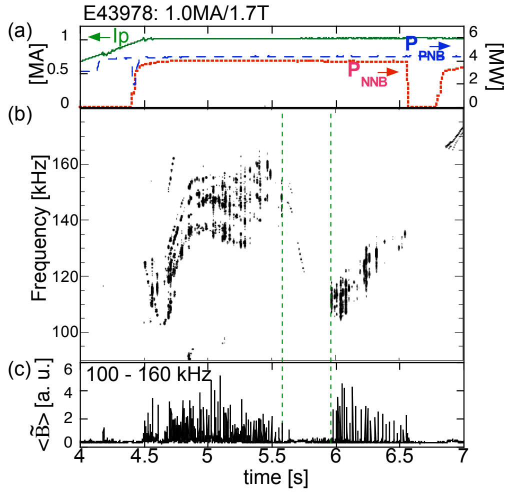

Fig.2 *Time traces of plasma parameters of E43978. (a): Plasma current, I_P, and beam injection power of N-NB and two units of P-NB for diagnostics of q-profile and ion temperature. The beam energy of N-NB and both P-NB is ~370 keV and and ~80keV, (b) Frequency spectrum of magnetic fluctuations. (c) Amplitude of magnetic fluctuations with frequency of 100-160 kHz.*

3. Property of Instabilities in NNB Injected Weak Shear Plasmas

Shown in Fig.2 are the waveforms of plasma parameters in the discharge described in Sec.2. Figure 2 (a) shows the time evolution of plasma current and injected NNB and PNB power. Figures 2 (b) and 2 (c) show the time traces of the frequency spectrum and mode amplitude with frequency of 100 - 160 kHz, respectively. An instability appears with a frequency of about 100 kHz at about 4.6 s and its frequency chirps up to about 150 kHz at about 4.8 s. After the saturation of the frequency sweeping from 4.8s to 5.5s, instabilities were almost stabilized for ~ 0.4 s from t ~ 5.5 s. Further another frequency sweeping started from t ~ 5.9 s. So far, such instabilities with frequency sweeping have been labeled as the slow Frequency Sweeping modes [16]. However, the cause of the mode has been not identified yet.

In order to understand the large and rapid frequency sweeping and its subsequent saturation in WS plasmas, we propose a model of RSAE and its transition to TAE as q_{min} decreases [14]. RSAE is a global AE near the zero shear region of the RS plasma. However, we consider RSAE can be applied to AEs with the large frequency sweeping in WS plasmas. Shown in Fig. 3 are the Alfvén continuum spectrum for n = 1 mode and the safety factor versus minor radius (r/a) at (a) t = 4.7s, (b) 5.3s and (c) 5.7s in the discharge shown in Fig. 2, respectively. Values of q_{min} in Fig. 3 are (a) 1.7, (b) 1.4 and (c) 1.2, respectively. Frequency gaps outside the region (r/a > ~ 0.7) are similar in all three figures. The gap structures around the q_{min} region, however, are entirely different even if change in q_{min} is small. Gaps shown in Fig. 3 (b) and (c) are the TAE gaps formed by toroidal coupling of the m = 2 and m = 1 harmonics around q = 1.5 locations. On the other hand, in Fig. 3 (a), there is no q = 1.5 and the continuum gap is formed due to the weak shear q-profile in center region. The lower continuum is due to the m = 2 harmonic and the upper continuum is due to m = 1. Around the upper and the lower boundary of this continuum around q_{min} (r/a ~ 0.0), AEs can be destabilized by large energetic ions pressure and its gradient as shown in Fig. 4. Shown in Fig. 4 is classical pressure profile of energetic ions calculated with

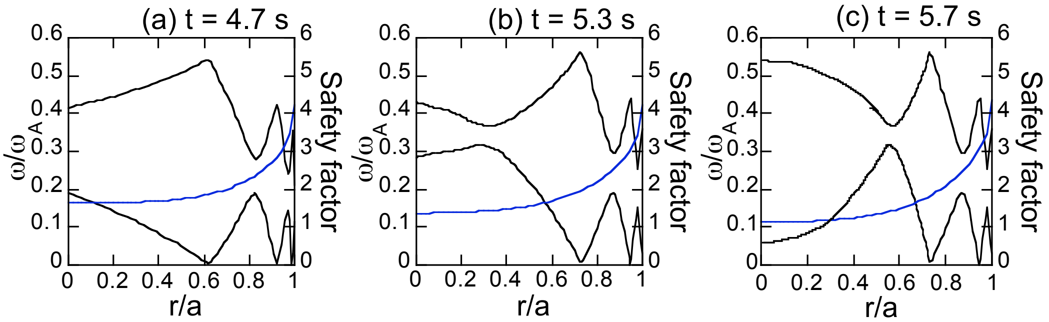

Fig.3 *Alfén continuum spectrum for n = 1 mode, safety factor profile at (a) 4.7s, (b) 5.3s and (c) 5.7s*

the OFMC code. A peaked pressure profile of NNB ions was produced with upper beam line shown in Fig.1. These modes can be called RSAE because the resonance condition for this mode is the same as for RSAE described in Ref.14. Therefore, 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 [14] :

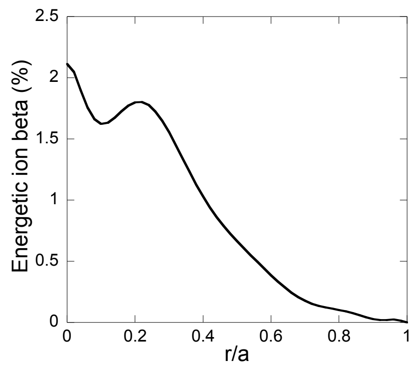

Fig.4 *Profile of classical energetic ion beta produced by NNB injection.*

(i) 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

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

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

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

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

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

where $c \sim r_{min}/nR$, 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. Here, we estimate frequency of RSAE and TAE for the case of the instabilities shown in Fig.2 (b) using eqs. 1-3, where R ~ 3.3 (m) $n_i(q_{min}) \sim 1.2\times10^{19}$ (m^{-3}), c ~ 0, B = 1.7T. The broken lines in Fig. 2 denote the estimated frequency. As shown in Fig. 2 (b), the large and rapid frequency sweeping and its subsequent saturation can be explained by RSAE and its transition to the TAE. On the other hand, any AEs are not observed although there is the TAE gap in the case of Fig. 3 (c). This is considered to be due to small pressure of energetic ion and its gradient around TAE gap (r/a ~ 0.5) as shown in Fig. 4. Thus, we show the property of AEs in WS plasmas by the RSAE model.

4. Confinement Degradation of Energetic Ions by RSAE and TAE

Figure 5 shows time trace of the frequency spectrum of magnetic fluctuation, the total neutron emission rate, neutral particle flux in energy of 20 ~500 keV and line integrated electron density.

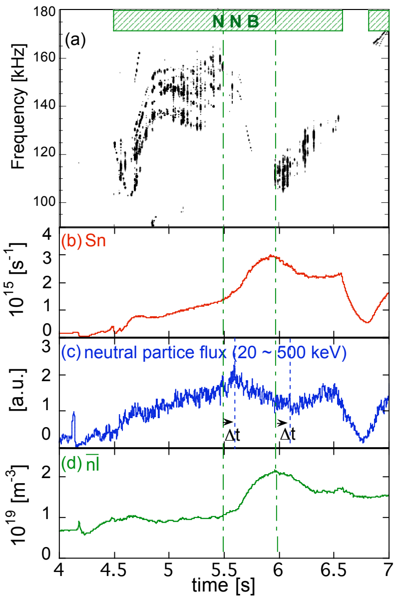

Fig.5 Time trace of (a) frequency spectrum of magnetic fluctuation (b) Total neutron emission (Sn) measured by Fission chamber. (c) charge exchange neutral particle flux of E ~ 20 - 500 keV. (d) Line averaged electron density (nl)

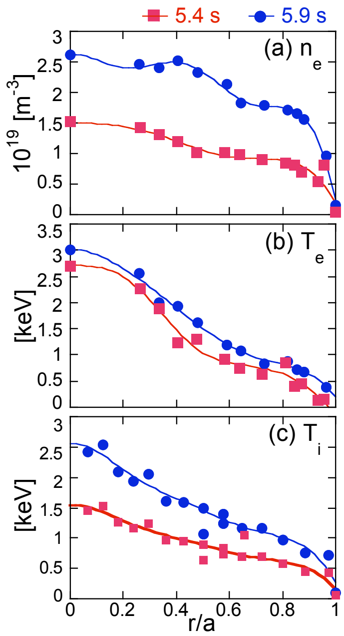

***Fig.6** Profiles of (a) electron density, (b) electron temperature and (c) ion temperature at 5.4 s (with AEs) and 5.9 s (without AEs)*

One can see that an increase of total neutron emission rate (Sn) seems to be suppressed in the presence of RSAE and TAE for t ~ 4.5 – 5.5 s. After TAE was stabilized at t ~ 5.5 s, the increasing rate of Sn is enhanced rapidly. However, Sn decrease after another RSAE appear after t ~ 5.9 s. On the other hand, CX neutral particle (CX-NP) flux increases for t ~ 4.5 – 5.5 s. Then, after ~ 100 ms from distablizing TAE, the CX-NP flux starts decreasing. Further the CX-NP flux increases again after ~ 100 ms from appearance of another RSAE. This time lag (Δt) the change in CX-NP flux for the change in Sn in Fig.5(c) can be explain by time scale of energetic ion transport due to AEs to outer region. Because the NDD detects energetic ions neutralized through charge exchange reactions with D^0 or C^{5+} in outer region of the plasma, Such changes in Sn and CX-NP flux suggest that energetic ions is transported due to these AEs. However, as can be seen in Fig. 5 (d), line averaged electron density changes in similar way as changes in Sn. Figure 6 shows radial profiles of (a) electron density, (b) electron temperature and (c) ion temperature with AEs (at t = 5.4 s) and without AEs (at t = 5.9 s), respectively. One can see that all parameters of bulk plasmas increase after AEs was stabilized. Because neutron emission rate depends on bulk plasma parameter, in particular is proportional to bulk ion density, the change in Sn might be dominantly due to changes in bulk plasma, not energetic ions.

Then, in order to evaluate how does confinement of energetic ions degrade, neutron emission rate is calculated with OFMC code, taking into account the changes in the bulk plasma. The calculation is performed assuming that the confinement of energetic ions is classical and the beam-target fusion reaction is dominant in total neutron emission rate. Actually, the beam-target neutrons account for ~ 90% of the total neutron emission in this discharge according to the calculation by TOPICS [21]. Shown in Fig. 7 (b) is measured total neutron emission rate (solid line) and calculated one with OFMC code (circle). Compared with both neutron emission rates, measured neutron emission rate is smaller than calculated one in the presence of RSAE and TAE. Whereas, after AEs are stabilized, measured neutron rate is close to calculated one, then consistent with that at t = 5.9 s. This result indicates confinement of

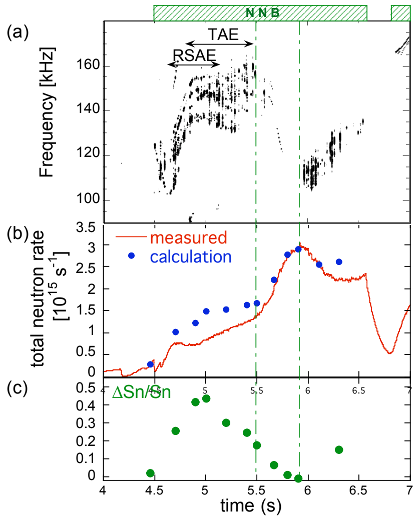

Fig.7 Time trace of (a) frequency spectrum of magnetic fluctuation, (b) measured neutron emission rate (solid line) and calculated one with OFMC code (circle) and (c) reduction rate of neutron emission rate (ΔSn/Sn).

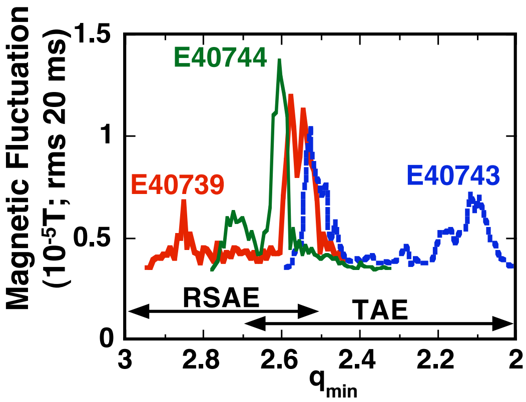

Fig.8 *Dependence of AE magnetic fluctuation amplitude on q_{min} in RS plasmas in three shots (E40739, E40743 and E40744). The n = 1 AE amplitude is enhanced in range of $2.4 < q_{min} < 2.7$ (Ref. 13)*

energetic ions is degraded due to RSAE and TAE. Further, it is considered that the difference between the measured one and the calculation one decreased after AEs disappeared because the confinement of energetic ions is close to classical. Figure 7 (c) shows time trace of reduction rate of neutron emission rate. This reduction rate is estimated from the ratio of calculated neutron rate to measured one. The reduction rate is large in the transition phase from RSAE to TAE from ~ 4.8 s to ~ 5.2 s, Here the maximum reduction rate is estimated $(\Delta Sn/Sn)_{MAX}$ ~ 45 % at t ~ 5.0s.

In the previous studies in JT-60U RS plasmas, it was observed in experimentally and predicted by numerical studies using TASK/WM code in theoretically that AEs are most unstable in the transition phase from RSAEs to TAEs [13]. Figure 8 shows the results of AE experiments in RS plasmas (I_p = 1.3 MA, B_t = 3.73 T). In these experiments, in order to investigate the dependence of mode amplitude on the q-profile change, the time of NNB injection was changed in three shots, where the values of q_{min} at the time of the NNB injection are about 3.0, 2.8 and 2.6 for the shots of E40739, E40744 and E40743, respectively. For all cases the n = 1 modes was observed and the amplitude was largest in the range $2.4 < q_{min} < 2.7$, whose range corresponded to the transition phase from RSAEs to TAEs, as shown in Fig.8. Thus understanding of the excitation mechanism of RSAE and its transition to TAE was progressed. However, effects of RSAE, TAE and the transition from RSAE to TAE on energetic ion confinement have been understood yet. In present study, confinement degradation of energetic ions in the presence of RSAE and TAE is evaluated for the first time.

5. Summary

In present work confinement degradation due to Alfvén Eigenmodes has been investigated with negative ion based injection WS plasmas on JT-60U. The AEs with a rapid frequency sweeping and then saturation as the minimum value of safety factor (q_{min}) decrease have been observed. These frequency behavior can be explained by RSAE and the transition from RSAE to TAE. The changes in total neutron emission rate and CX-NP flux suggested energetic ion transport due to these AEs. The reduction rate of total neutron emission rate in the presence of AEs is evaluated by calculation with Orbit Following Monte-Carlo code taking into account changing in bulk plasmas. The result indicates confinement of energetic ions is degraded due to AEs. In particular, it is found confinement degradation is maximum during transition from RSAE to TAE and the maximum reduction rate $(\Delta Sn/Sn)_{MAX}$ is estimated ~ 45 %.

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Reference

[1] CHENG, C.Z., CHANCE, M.S., Phys. Fluids **29** (1986) 3695.
[2] CHEN, L., et al., Phys. of Plasmas **1** (1994) 1519.
[3] WONG, K.L., et al., Phys. Rev. Lett. **66** (1991) 1874.
[4] STRAIT, E.J., et al., Plasma Phys. Control. Fusion 36 (1994) 1211.
[5] SAIGUSA, M., et al.,Plasma Phys. Control. Fusion **37** (1995) 295.
[6] KUSAMA, Y., et al., Nucl Fusion **39** (1999) 1837.
[7] ISHIKAWA, M., et al., accepted for Nucl. Fusion, (2005)
[7] SHINOHARA, K., et al., Nucl. Fusion **41** (2001) 603.
[8] ISHIKAWA, M., et al., Rev. Sci. Instru.**73** (2002) 4236.
[9] ISHIKAWA, M., et al., Rev. Sci. Instru.**75** (2004) 3643.
[10] Sharapov, S., et al., Phys. Lett. A **289**, (2001) 127.
[11] TAKECHI, M. et al., Annual Report of National Institute for Fusion Science, April 1999–March 2000, pp. 268, ISSN 0917-1185 (2000) .
[12] TAKECHI, M. et al., J. Plasma Fusion Res. **12**, (2002) 1273 .
[13] TAKECHI, M. et al., Plasam of Phys. **12**(2005).82509
[14] 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).
[15] Berk, L., et al., Phys. Rev. Lett. **87** (2001)185002 .
[16] SHINOHARA, et al., Nucl. Fusion **42** (2001) 603
[17] TANI, K., et al., Phys. Soc. Jpn. **50** (1981) 1726
[18] NISHITANI, T., et al., Rev. Sci. Instru. **63** (1992) 5270.
[19] KRASILNIKOV, A.V., et al., IEEE trans. Nucl. Sci. **45** (1998) 385.
[20] KRASILNIKOV, A.V., et al., J. Plas. Fusion Res. **75** (1999) 967.
[21] SHIRAI, H., et al., J. Phys. Soc. Jpn. **64** (1995) 4209.