Contributed Paper

Instability in the Frequency Range of Alfvén Eigenmodes Driven by Negative-Ion-Based Neutral Beams in JT-60U

SHINOHARA Kouji[1)], ISHIKAWA Masao[1)], TAKECHI Manabu[1)], KUSAMA Yoshinori[1)], TODO Yasushi[2)], GORELENKOV Nikolai[3)], CHENG Chio[3)], FUKUYAMA Atsushi[4)], KRAMER Gerrit[3)], NAZIKIAN Raffi[3)], MATSUNAGA Go[1)] and OZEKI Takahisa[1)]

[1)]Naka Fusion Research Establishment, Japan Atomic Energy Research Institute, Naka, Ibaraki, 311-0193, Japan

[2)]National Institute for Fusion Science, Oroshi-cho, Toki, Gifu, 509-5292, Japan

[3)]Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, New Jersey 08543, USA

[4)]Department of Nuclear Engineering, Kyoto University, 606-8501, Japan

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Alfvén eignemode experiments have been carried out by using the negative-ion-based neutral beam in JT-60U. For bursting instabilities in the frequency range of Alfvén Eigenmodes, two types of mode activity have been observed. In one type called Abrupt Large-amplitude Event (ALE), enhanced transport of the energetic ions was detected. The enhanced transport showed the clear energy dependence based on measurements performed using a natural diamond detector. In another type of bursting event called the fast Frequency Sweeping (fast FS) mode, frequency up-down chirping is observed on the time-scale of a few ms, much faster than equilibrium changes in the background plasma. This frequency chirping was well reproduced by the non-linear simulation code, MEGA, for magnetohydrodynamics (MHD) with energetic particles. The slow up-frequency sweeping of the Reversed-Shear-induced Alfvén Eigenmode (RSAEs), due to the slow evolution of $q_{\min}$ was also observed. These experiments were analyzed by using the NOVA-K code. It is shown that the most unstable modes are localized around the minimum in the magnetic safety factor ($q_{\min}$) in the analysis.

keywords:

Alfvén eigenmode, negative-ion-based neutral beam, tokamak, JT-60U, MEGA, non-linear activity, Reversed-Shear-induced Alfvén Eigenmode, NOVA-K

1. Introduction

In a reactor-relevant plasma, energetic ions, namely α particles, as a product of D-T fusion reactions may interact with the bulk plasma and may induce instabilities in the frequency ranges of Alfvén eigenmodes. Alfvén eigenmodes can enhance the transport of the energetic ions and may lead to the deterioration of the plasma performance, or lead to damage of plasma facing components [1]. Meanwhile, some authors suggest possibilities of usefulness for these instabilities, which are called "α-channeling"; one application is for plasma current profile control by controlling the transport of the energetic ions [2] while another is a bulk ion heating through Alfvén eigenmodes [3,4]. In order to more fully understand the potential of these instabilities to improve plasma performance, or to avoid deleterious effects from the excitation of these modes, we need to understand the characteristics and the mechanism of the wave-particle interactions.

So far, in experiments with energetic ions produced by high energy neutral beams (NB) or Ion-Cyclotron Range of Frequency (ICRF) heating, several instabilities in the frequency ranges of Alfvén eigenmodes have been observed [5]. Some of them have had a "steady" temporal behavior and have been identified; e.g. Global Alfvén eigenmode (GAE) [6,7], Toroidicity-induced Alfvén eigenmode (TAE) [8,9], Ellipticity-induced Alfvén eigenmode (EAE) [10], Noncircular triangularity-induced Alfvén eigenmode (NAE) [10], etc. in contrast to these steady frequency modes, several instabilities are observed with rapid frequency sweepings. One of frequency sweepings has been recently explained by the temporal evolution of $q_{\min}$, for Reverse Shear Alfvén Eigenmodes (RSAEs). (RSAE) [11-13] or Alfvén Cascade [14,15]. However, some frequency sweepings has a very short time scale, which cannot be explained by the temporal behavior of the bulk plasma and equilibrium, and are sometime called "frequency chirping modes" [16-18]. The instabilities of this type appear as bursts, namely each mode has a short duration, typically less than a few milli-second. The short-time-scale frequency sweeps are expected to couple with the temporal evolution of the distribution of energetic ions, though the detailed physics has not been fully understood yet.

author's e-mail: shinohak@fusion-naka.jaeri.go.jp

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In this article, recent research on instabilities in the frequency ranges of Alfvén eigenmodes in JT-60U is reported relating to the above issues. In the recent experiments, we used Negative-ion-based Neutral Beam (NNB) injection. NNB in JT-60U can be used to inject energetic neutral beam ions with energy of 300 – 400 keV tangentially in the same direction of the plasma current. Thus, we can investigate the characteristics of the modes and the transport of energetic ions induced in the ITER relevant regimes. This use of the NNB injection is one of unique characteristics of Alfvén wave research on JT-60U [19].

We describe some topics of bursting instabilities in the frequency range of Alfvén eigenmodes in Sec. **2**. In the bursting instabilities, we observed two types of modes phenomenologically. In one type, the mode duration was less than one milli-second and the mode amplitude was so large that we were able to detect enhanced transport of the energetic ions. The enhanced transport showed clear energy dependence. In another type, the mode amplitude is weaker compared with the first type of bursting mode. The frequency up-down chirping is clearly observed on the time-scale of a few milli-seconds. This frequency chirping was reproduced by the simulation code, MEGA [20].

In Sec. **3**., the observation of RSAEs is reported. RSAE comes from the analogy of GAE, which were mainly observed in cylindrical or helical systems. To demonstrate this ideal MHD model of the RSAE, we have performed experiments in the condition where we can measure the q profile with a high signal-to-noise ratio. We observed the slow up-frequency sweeping of the RSAE due to the evolution of $q_{\min}$, where $q_{\min}$ is the minimum of the value of safety factor profile. Recently, we also analyzed this experiment by using the NOVA-K code [8].

Finally, we summarize our findings in Sec. **4**.

2. Bursting Instability in the Alfvén Eigenmode Frequency Range

In most Alfvén eigenmode experiments using NNB injection, bursting instabilities are observed in the frequency range of Alfvén eigenmodes [17,18,21]. One example is shown in Fig. 1. Phenomenologically, we classified the bursting instabilities into two groups. The first one has a time-scale of a few milliseconds and its frequency sweeps upward and/or downward by 10–20 kHz in a few milliseconds. The starting frequency of this frequency sweeping lies in the TAE gap frequency. We named this group of modes fast Frequency Sweeping (fast FS) modes. On the occurrence of the fast FS mode, a small drop in the neutron emission rate, which suggests enhanced transport of energetic ions, was observed in several cases with relatively large mode amplitude measured by Mirnov coils [18]. The second bursting mode is named the Abrupt Large-amplitude Event, ALE. This mode has a time-scale of less than 1 millisecond. It is difficult to say whether the ALE always has a frequency sweeping, basically due to its short-time-scale behavior. However the ALE sometimes follows a frequency sweeping. The mode amplitude is large. The amplitude of magnetic fluctuations measured using Mirnov coils reaches $\tilde{B}_{\mathrm{pol}}/B_{\mathrm{pol}} \sim 10^{-4}$ at the wall. On the occurrence of the ALE, we observed drops in the neutron emission rate for the larger amplitude modes.

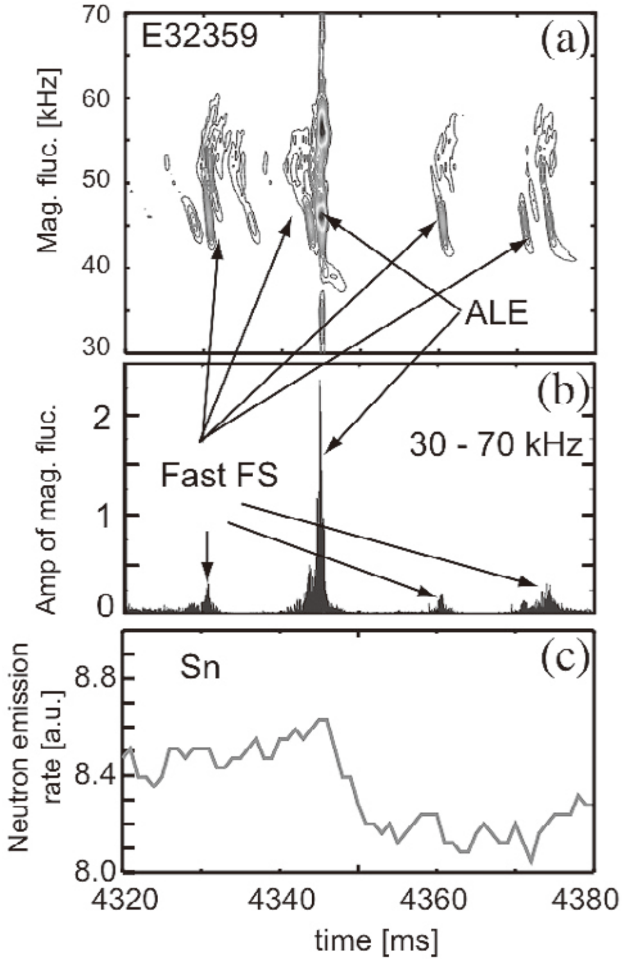

Fig. 1 Temporal evolutions of (a) frequency spectrum of magnetic fluctuations measured by Mirnov coil, (b) amplitude of magnetic fluctuations with frequency of 30 – 70 kHz, (c) neutron emission rate.

The enhanced transport of energetic ions has been observed during ALEs. An energy dependence of the enhanced flux of charge exchange neutral particles is measured using a E//B type neutral particle analyzer [22]. It is thought that the observed enhanced flux is produced by energetic ions transported to peripheral region of plasma where the neutral density is relatively large. The energy dependence suggests that enhanced transport of energetic ions is induced by a resonant wave-particle interaction [21]. Recently, we have installed a new charge exchange neutral particle flux measurement system by using natural diamond detectors (NDD) [23]. A clear bump in velocity space in the flux was observed, which enabled a clear identification of the resonant interaction [24]. We also estimated the change in the energetic ion population spatial profile by using a neutron emission profile monitor [25]. The estimated change of the energetic ion spatial profile induced by a large ALE is shown in Fig. 2. [24].

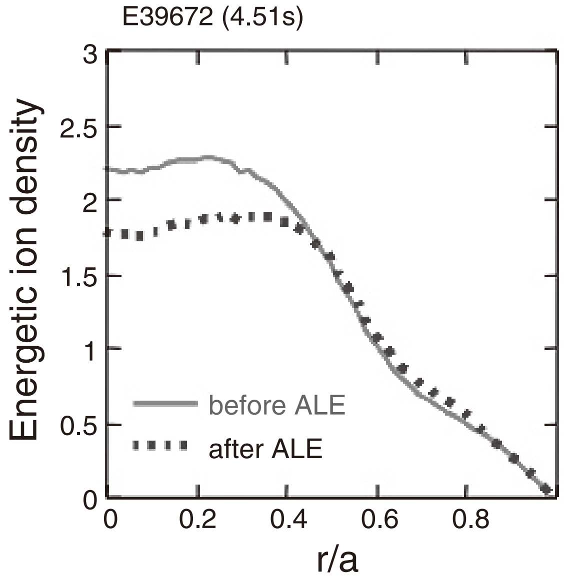

Fig. 2 Fast ion density profiles before and after ALE. These profiles are derived from the data obtained by a neutron profile monitor.

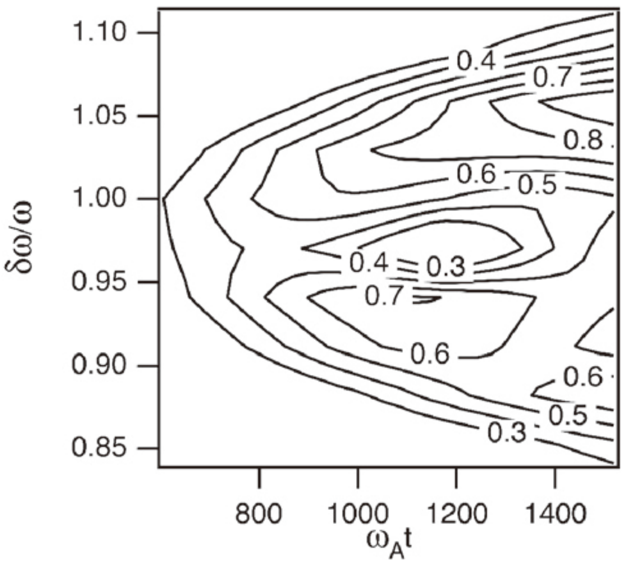

Fig. 3 Temporal evolution of frequency spectrum of radial magnetic field fluctuations in simulation by MEGA code.

The fast FS mode in a JT-60U plasma has been studied using the nonlinear MEGA code for magnetohydrodynamics (MHD) and energetic particle simulation. The plasma is divided into two parts; energetic ions and bulk plasma in this code. The bulk plasma and the electromagnetic field are described by the MHD equations and a drift-kinetic description is employed for the energetic ions. To complete the equation system in a self-consistent way, the energetic ions affect the bulk plasma through the MHD momentum equation via the energetic ion current. The δf particle simulation method was applied to the energetic ions. The frequency chirping of fast FS mode was reproduced by the simulation code [20]. The results are shown in Fig. 3 [26]. The mechanism of frequency chirping is considered to be due to "spontaneous hole-clump pair creation". In Ref. [27], the spontaneous hole-clump pair creation appear when $\gamma_d/\gamma_L > 0.4$, where γ_d is the linear damping rate and γ_L is the linear growth rate. In our simulation, the ratio γ_d/γ_L is 0.68. From the analysis using the MEGA code, the fast FS mode is considered not to be a TAEs but to be an Energetic Particle Mode (EPM) which is located near the center of the plasma where the energetic ion density is highest [28]. The mode structure measurement is an issue for future consideration. The EPM is a mode, which is strongly affected by the energetic ion population. It is expected that the behavior of Fast FS mode could be changed when the energetic ion density profile is changed in the experiments. The frequency behavior of fast FS was compared with the neutron emission profile measurement. Figure 4(a) shows a temporal evolution of magnetic fluctuations. During the time period from 4.2 to 4.3 s, upward frequency sweeping FS are dominant. On the other hand, up and downward FS are observed during the time period from 4.4 to 4.5 s, though the start frequency of Fast FS is almost same as that in the earlier time period. The time separation between ALEs is also longer in the later time

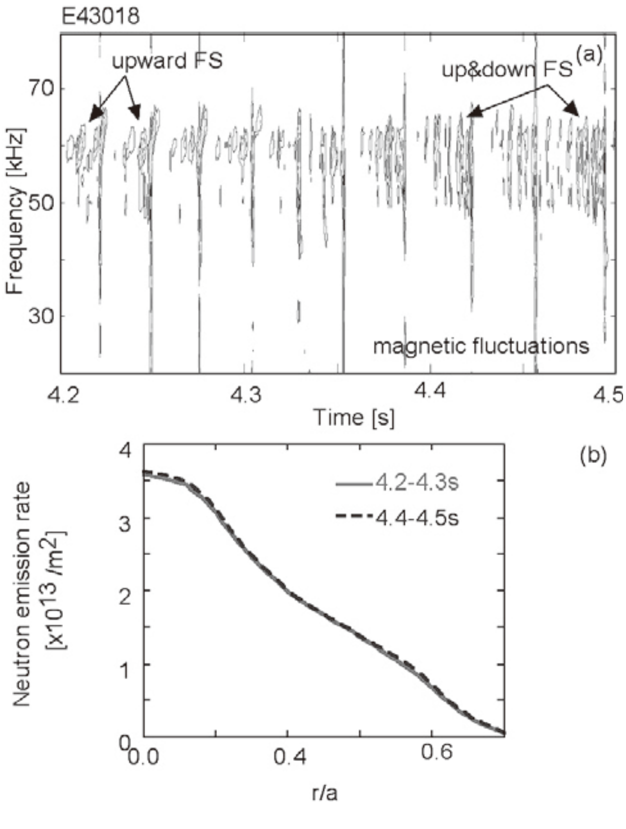

Fig. 4 (a) Temporal evolution of frequency spectrum of magnetic fluctuations. (b) Time averaged neutron emission profiles measured by neutron profile monitor for two time intervals of t = 4.2s to 4.3s and t = 4.4s to 4.5s.

period. In the period from 4.2 to 4.5 s, the equilibrium plasma parameters and profiles do not change significantly, except for the toroidal rotation. The toroidal rotation changes from ~20 km/s to ~40 km/s, which corresponds to the change in the mode frequency of the n = 1 mode from ~1 to ~2 kHz. The time-averaged neutron emission profiles are depicted in Fig. 4 (b). The time average was carried out from 4.2 to 4.3s and from 4.4 to 4.5 s. A difference was barely noticeable in the neutron emission profile.

As discussion, we present the following speculations. First a small change in the toroidal rotation might change the behavior of the frequency sweeping through the change in the damping or driving of the mode because the balance between damping rate and growth rate is considered to be important in some fast frequency change activities [27]. There are reports in which TAEs are suppressed, namely the damping rate of the TAE was increased, by changing the toroidal rotation [29,13]. A similar mechanism might be working in our observations and these changes in damping and drive may affect the nonlinear behavior with more sensitive manner in this nonlinear activity. Alternatively, structures in the energetic ion density profile in time and/or space can play an important role in the driving and damping mechanism. Fine structures of the energetic ion density profile in time and/or space might be important, e.g. a local steepening in the gradient that could not be measured at present, might affect the driving mechanism of these modes. A third suggestion is that a small change in the thermalized plasma might change the damping of the mode as some part of the damping can come from the thermalized plasma, such as ion Landau damping.

3. Reversed-Shear-Induced Alfvén Eigenmode

Alfvén eigenmodes in reversed shear plasmas were investigated by using the kinetic full-wave TASK/WM code and the model of Reversed-Shear-induced Alfvén Eigenmode (RSAE) was proposed to explain these observations [11,13]. In reversed shear plasmas, a spectral gap is induced around the position of the minimum of the magnetic safety factor, ρ_{qmin}. The RSAE is excited in this gap, and that the mode consists of a single poloidal mode number similar to the Global Alfvén Eigenmode (GAE). The frequency of the RSAE lies just below the upper continuum of the gap and just above the lower continuum as shown in Fig. 5. Thus the frequency is approximately expressed as ~ $(n - m/q_{\mathrm{min}})v_{\mathrm{A}}/2\pi\mathrm{R}$ for the upper mode and ~$(m/q_{\mathrm{min}} - n)v_{\mathrm{A}}/2\pi\mathrm{R}$ for the lower frequency mode, where n is the toroidal mode number, m is the poloidal mode number, v_{A} is the Alfvén velocity and R is the major radius. From this expression, we notice that the mode frequency is sensitive to the value of q_{min}. It is expected that this q_{min} dependence lead to the frequency sweeping of the mode when the q_{min} is changing in the reversed shear discharge.

RSAE experiments using NNB injection have been carried out on JT-60U [12]. Figure 6 shows magnetic fluctuation spectra from experiment. An $n = 1$ mode was observed at the expected RSAE frequency. The mode was identified as an RSAE from the comparison among the observed temporal evolution of the mode frequency, the mode amplitude, and the temporal evolution of the gap structure by the simplified model calculation.

Here, we show the stability analysis of the observed mode using NOVA-K code. The NOVA-K code evaluates the growth rate of Alfvén eigenmodes due to kinetic effects using perturbative analysis. In addition to the driving terms, the NOVA-K code calculates the damping rates, such as thermal electron and ion Landau damping, and the trapped electron collisional damping with finite orbit width (FOW) and finite Larmor radius (FLR) effects [8,30,31]. Furthermore, the treatment of the anisotropic beam ion produced by neutral beam injection was improved recently [32]. In this analysis, we use

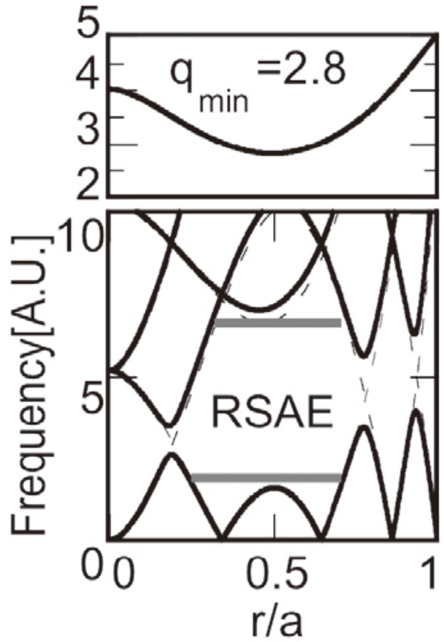

Fig. 5 Schematic drawing of Alfvén continuum spectra for $n = 1$ in the RS plasma with $q_{\mathrm{min}} = 2.8$. Here, the broken curves stand for Alfvén continua in a cylindrical plasma.

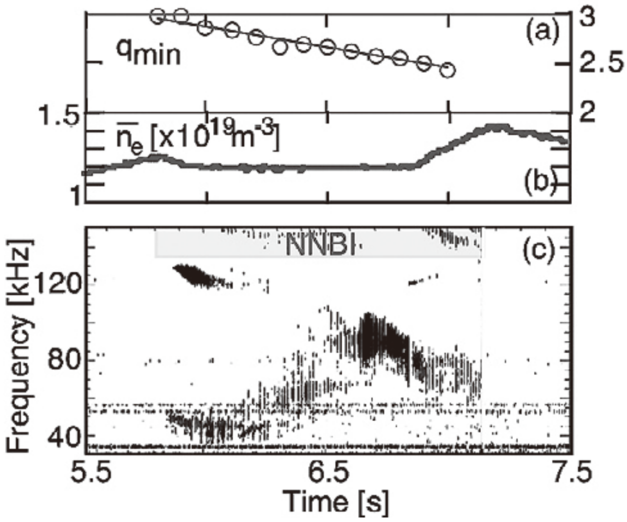

Fig. 6 (a) Temporal evolution of q_{min}, (b) line averaged electron density, (c) a time trace of frequency spectrum of the $n = 1$ instability. Note: three horizontal vague lines around 48 kHz and 36 kHz in the figure come from noise in Mirnov coil system.

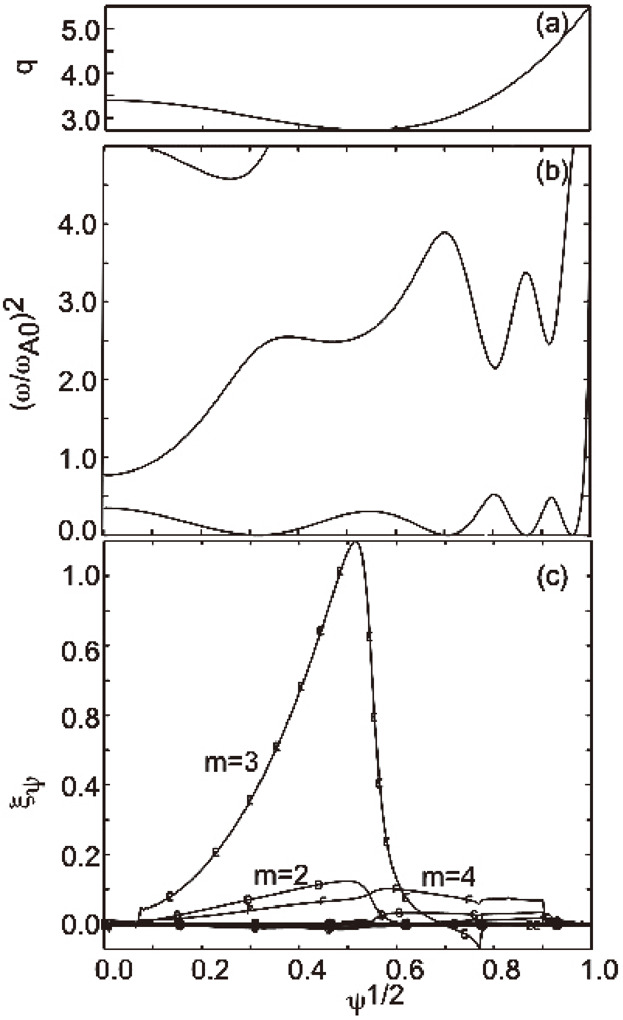

Fig. 7 (a) q profile, (b) continuum spectrum of n = 1, (c) mode structure with similar mode frequency to the experiment in Fig. 6.

this latest version of NOVA-K code.

The energetic ion parameters using in NOVA-K are based on the OFMC code calculation, in which the enhanced transport induced by MHD is not taken into account. Namely, the value taken is the so-called classical value [33].

Figure 7(a), (b) and (c) show the q profile, the continuum spectrum for n = 1 and the calculated mode structure for the most unstable mode at t~ 6.5 s in Fig. 6, respectively. Here, $\omega_{A0} = B/q_s R\sqrt{n_{i0}M_i}$ and n_{i0} is the central ion density and M_i is the ion mass. The value $(\omega/\omega_{A0})^2$ of the most unstable mode is 0.3112, which is similar to the experimental value of 0.33–0.36. As expected, we can see that the mode is localized around ρ_{qmin} for q_{min}~2.8, and that the mode with the single poloidal mode number of m = 3 is dominant.

The stability curve (open circles), which is the boundary where the damping rate overcomes the growth rate in the domain of central fast ion beta, β_{h0}, and $v_{b//}/v_A$ is depicted in Fig. 8. An important note for this analysis is that continuum damping is not included. Thus, the damping rate and critical energetic ion beta are underestimated.

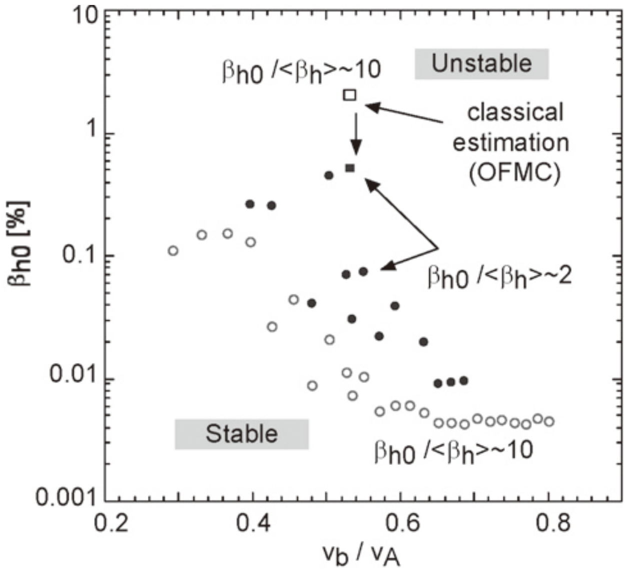

Fig. 8 Stability curve (circles) in the domain of central energetic ion beta, β_{h0}, and v_b/v_A. Open markers are for classical estimation, by OFMC code, of $\beta_{h0}/\langle\beta_h\rangle$~10, and closed markers are for assumed parameter of $\beta_{h0}/\langle\beta_h\rangle$~2. Square symbols mean assumed parameters of beam ions for the experiment; open square for classical estimation and closed square for the profile of the reduced peaking factor of $\beta_{h0}/\langle\beta_h\rangle$~2.

The open square symbol in Fig. 8 represents the beam ion parameter by classical estimation using the OFMC code for the experimental parameters. The critical β_{h0} is much smaller than the value of β_{h0}, open square in Fig. 8, of the OFMC calculation at $v_{b//}/v_A$~0.53 where experiments are carried out. However, the mode activity was moderate in the experiments and the experiment parameter seems to be marginal. There seems a large difference between the stability curve and the OFMC estimation, which might come from an excessively peaked fast ion profile in the OFMC result or from the lack of continuum damping in the calculations. It is expected the fast ion profile should be modified due to the enhanced transport induced by the mode but no direct confirmation is possible so far. We carried out the stability calculation with a reduced fast ion peaking factor (by about 5), keeping $\langle\beta_h\rangle$ the same. The stability boundary in this case (closed circle) increased and came closer to the reduced β_{h0}. The energetic ion profile, estimated using the neutron profile monitor and profile information of the thermalized plasma, might give us some more information on the fast ion beta, however we do not have such data so far. Thus this is an interesting future issue to be clarified. The inclusion of continuum damping is also an important issue.

4. Summary

Bursting modes in the frequency range of TAEs were observed during NNB injection in JT-60U. To investigate the transport of energetic ions under the presence of ALEs, neutron emission profile measurements were performed. The neutron measurements showed the redistribution of energetic ions by ALEs. Energetic ions in the center region of the plasma were expelled significantly to the outer region. We also observed the clear energy dependence of the loss from the core by using a new diagnostics; the natural diamond detector. In another type of bursting mode called fast FS mode, the frequency up-down chirping is observed on the time-scale of a few ms. This frequency chirping was reproduced by the newly developed simulation code, MEGA.

To understand the physics of Reversed-Shear-induced Alfvén Eigenmodes, RSAE, we performed experiments in conditions where the q profile could be accurately measured with a good signal-to-noise. We observed the slow up-frequency sweeping of the RSAE due to the downward evolution of $q_{\min}$. This experiment was analyzed using the NOVA-K code. We observed that the most unstable mode was localized near $q_{\min}$ with a single dominant poloidal mode number.

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