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Characteristics of Tearing Modes in Steady State High β_p H-mode Discharges in JT-60U

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Abstract

In the steady state high β_p mode discharges in JT-60U, long sustainment of the beta plasma is limited by the occurrence of tearing modes with low toroidal and poloidal mode numbers. In this paper, characteristics of the tearing modes are described mainly from the viewpoint of the experimental results. It is found that the characteristics are similar to those of the neoclassical tearing mode. Tearing mode stabilization experiments have been carried out since 1999 by local heating and current drive using the newly installed electron cyclotron wave injection system. Although decrease in magnetic perturbations and electron temperature perturbations was observed, complete stabilization was not successful.

Keywords:

high β_p mode, edge localized mode, tearing mode, neoclassical tearing mode, electron cyclotron heating, electron cyclotron current drive, tokamak

1. Introduction

In a fusion reactor, impurities including helium ash must be exhausted from the core plasma since they can reduce the fusion reactivity. An operational scenario utilizing an edge localized mode (ELM) is considered to be most promising since the impurities can be exhausted from the plasma without significant degradation of the plasma performance. In the International Thermonuclear Experimental Reactor (ITER), ELMy H-mode is considered to be a standard operational scenario.

In the steady state high β_p mode discharge in JT-60U, an ELMy H-mode state with $\beta_N \approx 2.0$ and $H \approx 2.3$ is sustained for 4.5 s. And $\beta_N \approx 1.8$ and $H \approx 1.7$ is sustained for 9 s [1]. Here, β_N is the normalized beta and H is the confinement enhancement factor for the ITER 89P L-mode power law (H-factor). In a series of the discharges, pressure profile and heating profile are optimized to sustain the high performance plasma for a long time. It is known that if the pressure profile is too peaked, the performance is limited by the occurrence of a beta collapse. On the other hand, if the pressure profile is too broad, the performance is saturated by giant ELMs [2]. Thus, the pressure profile with medium peakedness is preferable for the steady state high β_p H-mode discharge. However, under such an optimized condition, the plasma performance is limited by the occurrence of low-n resistive modes with n = 1 to 3 in the higher beta region. Typically tearing modes with m/n = 3/2 and/or 2/1 are observed. Here, m and n are poloidal and toroidal mode numbers, respectively. From a stability analysis, it was shown that in one of the typical steady state high β_p mode discharges, the tearing mode was destabilized even when $\Delta' < 0$. Here, Δ' is the tearing parameter. In the discharge, magnetic island width measured by an ECE heterodyne radiometer

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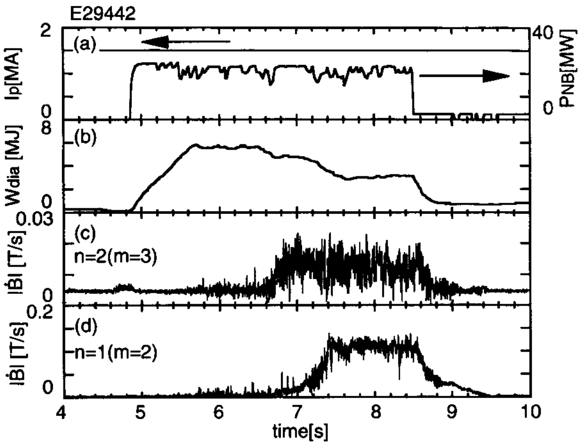

Fig. 1 Typical waveform of a steady state high β_p H-mode discharge. (a) Plasma current and NBI power, (b) stored energy, (c) magnetic perturbation with $n = 2$, (d) magnetic perturbation with $n = 1$.

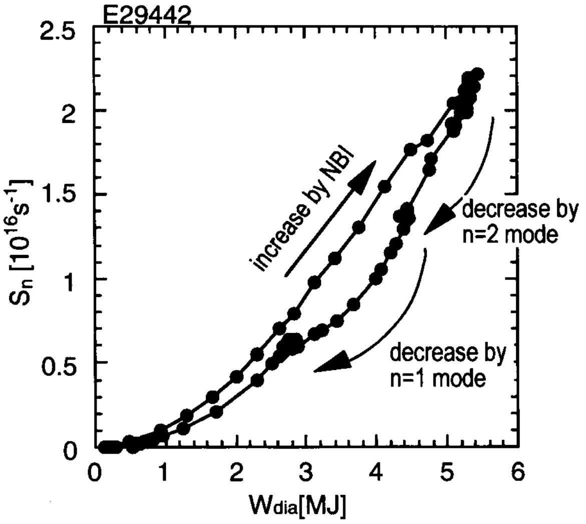

Fig. 2 Relationship between neutron emission rate and stored energy.

showed that it was comparable to that predicted by the neoclassical tearing mode theory [3].

Similar kinds of tearing modes are observed in other tokamaks such as ASDEX-U [4] and DIII-D [5]. It is said that the tearing modes are caused by bootstrap current. They are referred to as neoclassical tearing modes.

In this paper, characteristics of the tearing modes, mainly from the viewpoint of experimental results, are described comparing with those of the neoclassical tearing modes. After this introduction, overview of the steady state high β_p H-mode discharge is described in section 2. The characteristics of the tearing modes are described in section 3. In section 4, initial results of the tearing mode stabilization experiment by local heating/ current drive using electron cyclotron wave injection are described. Summary of this paper is described in section 5.

2. Steady State High β_p H-Mode Discharge

The high β_p H-mode plasma is characterized by a q-profile with $q(0) > 1$, and the thermal transport barrier appears at a weak positive magnetic shear. A typical waveform of the steady state high β_p H-mode discharges is shown in Fig. 1. At $t = 4.85$ s, NB power of 23 MW is injected and the beta value increases. The plasma enters an ELMy H-mode state. At $t = 5.7$ s in this discharges, plasma parameters are as follows: plasma current $I_p = 1.5$ MA, toroidal field $B_t = 3.7$ T, major radius $R = 3.2$ m, minor radius $a = 0.8$ m, safety factor at the 95% flux surface $q_{95} = 4.0$, triangularity $\delta = 0.14$, elongation $\kappa = 1.5$, plasma volume $V_p = 54$ m^3, line-averaged electron density is 2.1×10^{19} m^{-3}, stored energy measured by diamagnetic loops $W_{dia} = 5.6$ MJ, poloidal beta $\beta_p = 1.8$, normalized beta $\beta_N = 2.5$, internal inductance $l_i = 1.2$. At $t = 6.5$ s, an $m/n = 3/2$ mode grows up, and stored energy decreases. At $t = 6.7$ s, an $m/n = 2/1$ mode grows up, and stored energy further decreases. The stored energy after the saturation of the 2/1 mode is half as large as that before the appearance of the 3/2 mode. Relation between the stored energy and then the neutron emission rate is shown in Fig. 2. As shown in this figure, if the instability occurs, degradation of the neutron emission rate, which means the degradation of the fusion reactivity, is more serious.

3. Characteristics of The Tearing Modes

The neoclassical tearing mode is different from the 'classical' tearing mode in that a) the mode is destabilized even when $\Delta' < 0$, b) magnetic island width increases with the beta value, c) onset β_N has positive dependence on density and collisionality, d) hysteresis exists in the beta value at which the tearing mode appears and that at which the mode disappears, e) some kind of MHD event, such as sawtooth and ELM, is needed for the seed island formation [6]. We will compare the above characteristics with the experimental results.

From a sequence of the steady state high β_p mode discharges, it was found that the onset β_N has positive

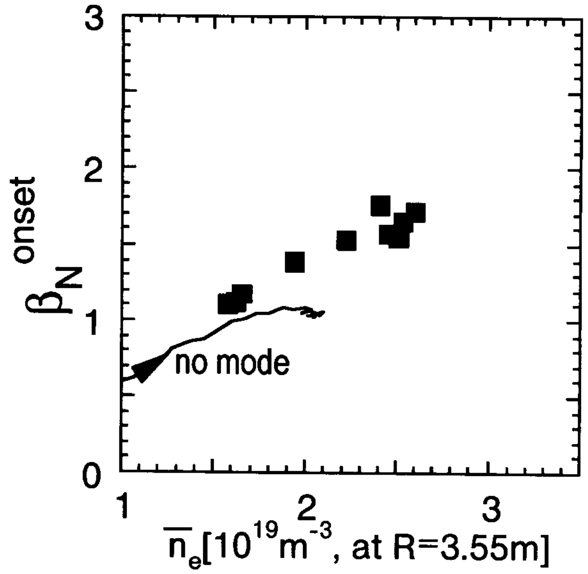

Fig. 3 Density dependence of onset β_N for an m/n = 3/2 mode.

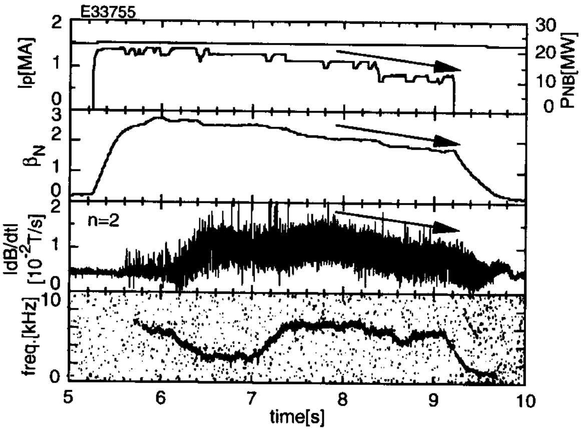

Fig. 4 Waveform of (a) plasma current and NBI power, (b) normalized beta, (c) amplitude of magnetic perturbation with n = 2, (d) mode frequency during NB power-down.

dependence on electron density [3]. In order to investigate the density dependence of the onset more precisely, the onset β_N is investigated with a fixed plasma configuration. The density dependence of the onset β_N for an m/n = 3/2 mode is shown in Fig. 3. In this systematic scan, electron density was changed by changing the gas puff rate and NB power. Other conditions are fixed as follows: I_p = 1.5 MA, B_t =3.7 T, R = 3.2 m, a = 0.8 m, q_{95} = 4.0, δ = 0.14, κ = 1.5 and V_p = 55 m^3. As shown in this figure, the density

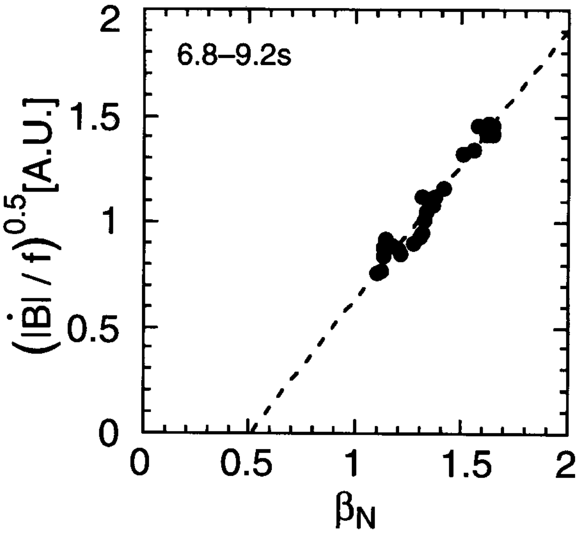

Fig. 5 Relation between $(|\dot{B}|/f)^{0.5}$ and β_N.

dependence is confirmed more clearly. The curve in Fig. 3 was obtained in a shot where no mode was observed. In this shot, the attained beta was slightly lower because injected NB power was lower. This result shows the existence of the threshold of the mode onset, and also shows that the plasma becomes more unstable in higher beta region. This trend is the same as that of the neoclassical tearing mode.

Another distinctive characteristic of the neoclassical tearing mode is that saturated island width increases with the beta value. If the neoclassical effect is not included, the saturated island width decreases with increasing the beta value because of the Glasser, Greene and Johnson effect [7]. In order to investigate the dependence, NB injection power was slightly decreased after the amplitude of the tearing mode is saturated. The waveform is shown in Fig. 4. At t = 6.1 s, an m/n = 3/2 mode grows up. At t = 6.5 s, the beta value is slightly decreased by reducing the NB injection power. Relation between the normalized beta and $\{(dB/dt)/f\}^{0.5}$ is shown in Fig. 5. Here, f is frequency of the tearing mode. Thus, $\{(dB/dt)/f\}^{0.5}$ is a measure of the magnetic island width. The value of $\{(dB/dt)/f\}^{0.5}$ linearly decreases as the normalized beta decreases. Note that change in current profile and pressure profile which must be included for detailed analysis is not considered in this evaluation.

As shown in Fig. 1 and Fig. 4, once the tearing mode appears, it persists until the beta becomes low value. Typically, the beta value at which the tearing mode appears is at least twice as high as that at which it disappears. This suggest that hysteresis exists in the beta value at the mode onset and that at the mode disappearance. This kind of hysteresis is observed in many of the steady state high β_p mode discharges.

So far, most of the results show the characteristics of the neoclassical tearing modes. However, it is not clarified what forms the seed island. According to the neoclassical tearing mode theory, seed island is needed for the neoclassical tearing mode to be destabilized. The seed island is formed some kind of MHD event such as a sawtooth oscillation or a fishbone instability or an ELM. Error field can also form the seed island. In JT-60U, neither sawtooth oscillation nor fishbone instability is observed in this series of discharges. Thus, one of the candidates is an ELM. Further investigation for this problem is needed.

4. Stabilization of The Tearing Mode

It is necessary to stabilize the tearing modes to recover the plasma performance. In 1999, a new ECH/ ECCD system was installed, which can inject radio frequency wave of 110 GHz, and the maximum injection power is about 750 kW (1 MW at the gyrotron output). Toroidal injection angle is fixed at about 20°, and poloidal injection angle can be changed by rotating the steerable mirror [8].

In order to stabilize the tearing mode, it is also necessary to identify the mode location. It was shown that the location can be identified by measuring electron temperature perturbation measured by an ECE heterodyne radiometer [3]. The number of channels of the heterodyne radiometer is 24, and typical spatial resolution is about 2 cm in major radius, and the maximum temporal resolution is 1 μs. As shown in Fig. 6, the injection angle of the EC wave was adjusted so that the wave can be deposited at the center of the magnetic island.

Typical waveform of magnetic perturbations and electron temperature perturbations are shown in Fig. 7. In this discharge, a tearing mode with m/n = 3/2 exists continuously before the EC wave injection. The center of the magnetic island locates around R = 3.63 m. The operational region was chosen so as to reach the threshold of the mode onset shown in Fig. 3. In this discharge, the frequency of the tearing mode was about 6 kHz. As shown in this Fig. 7(b), amplitude of magnetic perturbations slightly decreases during the EC wave injection. Amplitude of electron temperature perturbation near the magnetic island also decreases as shown in Fig. 7(d). These results suggest a sign of the tearing mode stabilization by the EC wave injection. However, complete stabilization has not been achieved so far. In 2000, the tearing mode stabilization experiment will be performed with higher EC wave injection power (≈2.3 MW).

5. Summary

Characteristics of tearing modes in the steady state high β_p mode discharges are described mainly from the

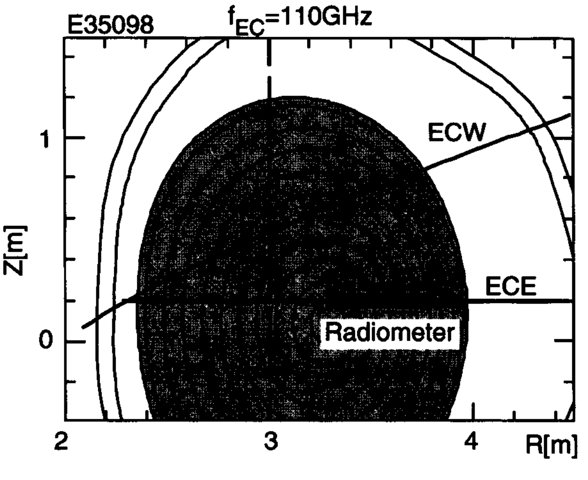

Fig. 6 Plasma configuration in a tearing mode stabilization experiment. Ray of EC wave and measurement range of the heterodyne radiometer are also shown.

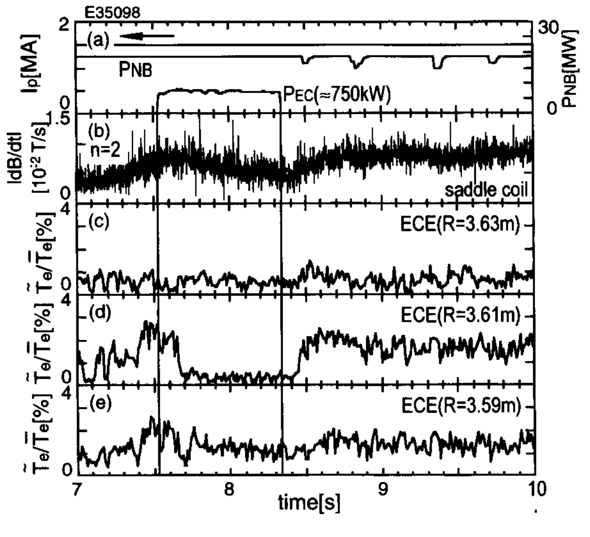

Fig. 7 (a) Plasma current, NB injection power and EC wave injection power. (b) Amplitude of magnetic perturbation with n = 2. (c)-(e) Amplitude of electron temperature perturbation.

viewpoint of the experimental results. The characteristics are similar to those of the neoclassical tearing mode:

a) Onset β_N increases with electron density.
b) The mode becomes more unstable with increasing beta.
c) Amplitude of saturated magnetic perturbations decreases when the beta value was decreased slowly.
d) Hysteresis exists in the beta value at the mode onset and that at the mode disappearance.

However, MHD event for the seed island formation, which is needed if the tearing mode in the high β_p mode discharges is the neoclassical tearing mode, is not identified. A plausible candidate is an ELM.

The tearing mode stabilization experiment was carried out by using the newly installed EC wave injection system. Although slight decrease in the magnetic perturbations and the electron temperature perturbations near the magnetic island was observed during the EC wave injection, complete stabilization was not achieved yet.

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