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On MHD Oscillations in High Beta H-Mode Tokamak Plasma in JFT-2M

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Abstract

In the recent high beta H-mode experiments in JFT-2M tokamak, total beta value above ~2.5% is obtained. The high performance plasma is obtained in high density region (normalized density ~1) with high triangularity ~0.7 in the limiter configuration. Suppression of the low frequency (< 10kHz) MHD (magnetohydrodynamic) oscillations is very important to obtain such high beta plasma. We find a stabilization of low mode MHD oscillation by current profile control by ramp-up of plasma current, counter neutral beam injection and inward shift of the plasma column. In the study of MHD oscillations in the edge transport barrier, we observe precursor MHD oscillations in density before the intermittent ELMs (edge localized modes), or two kinds (low frequency and high frequency) of characteristic quasi-coherent MHD oscillations (~ 70kHz to ~ 310kHz) in density, or in magnetic field, or in potential. These quasi-coherent modes are not found in the ELM-free H-mode phase but appear in the slightly degraded H-mode phase (H'-mode) or in enhanced D_α phase. A comparison of these quasi-coherent MHD with background turbulent fluctuation level is presented.

Keywords:

MHD oscillation, high beta, H-mode, EDA mode, ITB, ETB, JFT-2M, Tokamak, quasi-coherent mode, turbulence

1. Introduction

To achieve the high beta plasma is indispensable for the realization of the thermonuclear fusion reactor. In such a high beta plasma, various MHD oscillations appear according to the evolution of plasma current density profile and pressure profile during the course to achieve the high beta plasma. We present the recent observation of such MHD oscillations, whose frequency ranges from a few kHz to a few hundred kHz, observed in the course to obtain high beta H-mode in the JFT-2M tokamak in section 2.1, and in the study of the edge transport barrier (ETB) in section 2.2.

JFT-2M tokamak is a medium size tokamak (R = 1.31m) with non-circular cross section ($a \times b$ = 0.35m × 0.53m). The maximum toroidal field and plasma current are 2.2T, 0.5MA, respectively. The vacuum chamber is made of SUS with inner wall made of thin (~10mm) ferritic steel (F82H). The limiter is made of graphite. The wall conditioning is done by baking, Taylor discharge cleaning, boronization (Tri-methyl-boron) and daily He glow discharge cleaning. The two co- and counter-neutral beams are injected obliquely (~38° to the toroidal direction) for the additional heating in these experiments. The beam energy is 32keV and the total power is up to ~1.5MW.

2. Experimental results

2.1 MHD in high triangularity limiter H-mode

High elongation κ and high triangularity δ is preferred for obtaining high beta, because in these configuration, one can raise the total plasma current with the same toroidal field, namely the operation in the high normalized current $I_p/a/B_{to}$~0.8 is possible. Edge stability is improved in high δ. We attained κ~1.7, δ~0.7 (Fig. 1(a)) by increasing the push of the plasma by increasing the OH (ohmic heating) coil current. By the combination of the current ramp-up and neutral beam heating (NBH), successive counter-injection first and co-injection next, we could get weak shear configuration in which $1<q(r)<2$ in the plasma core region ($r/a<0.65$) (Fig. 1(b)). Therefore the plasma is sawteeth-free and we could get normalized beta β_N~3.2 (β_t~2.5%) with H factor ~1.5, β_N H~4.8, the Greenwald density ~ 0.95 ($\langle n_e \rangle$~0.7×10^{20}m^{-3}). The

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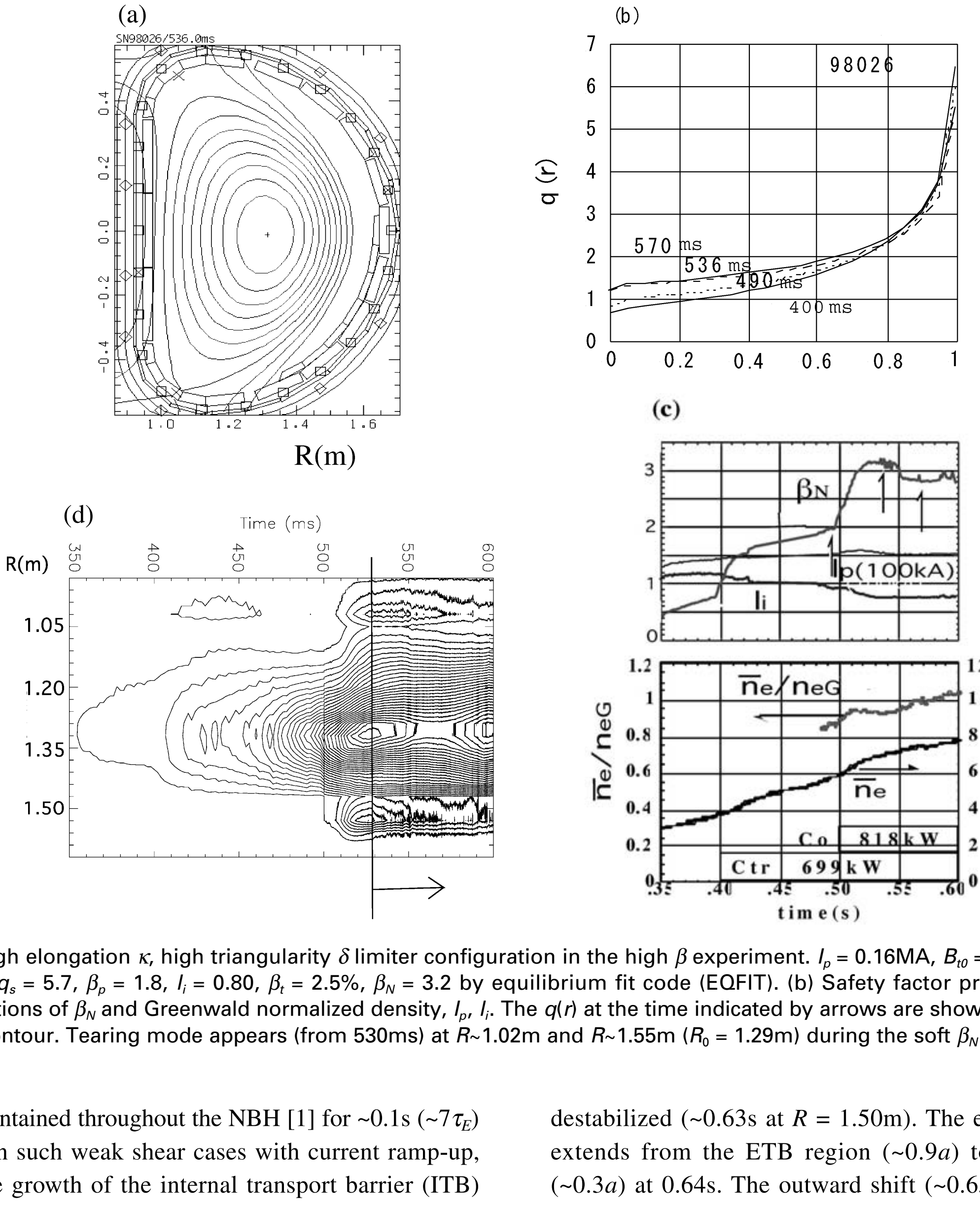

Fig. 1 (a) High elongation κ, high triangularity δ limiter configuration in the high β experiment. I_p = 0.16MA, B_{t0} = 0.77T, κ = 1.7, δ = 0.66, q_s = 5.7, β_p = 1.8, l_i = 0.80, β_t = 2.5%, β_N = 3.2 by equilibrium fit code (EQFIT). (b) Safety factor profile $q(r)$. (c) Time evolutions of β_N and Greenwald normalized density, I_p, l_i. The $q(r)$ at the time indicated by arrows are shown in (b). (d) Soft X-ray contour. Tearing mode appears (from 530ms) at R~1.02m and R~1.55m (R_0 = 1.29m) during the soft β_N degradation.

state was maintained throughout the NBH [1] for ~0.1s (~7τ_E) (Fig. 1(c)). In such weak shear cases with current ramp-up, we found the growth of the internal transport barrier (ITB) [2] which was characterized by rapid linear increase in core pressure accompanied by the slight decrease in the outer pressure by PIN diode array measurement.

There is a soft degradation in β_N from 0.55s. We observe low frequency tearing mode (f~6kHz) grows at the outer part r~0.7a near q = 2 surface (Fig. 1(d)). It seems that by the decrease in β_N, the mode activity decreases at ~0.57s.

The tearing mode seems to affect the quality of the ITB and ETB as shown in the next case with sawteeth oscillation (co-NBH first then ctr-NBH case) with q = 1 rational surface in the plasma as shown in Fig. 2. With the sawteeth, usually we cannot obtain high β plasma. In this case, by the inner shift of the plasma column, a sudden increase of the stored energy (~0.61s) by the formation of the ITB occurs even with the sawteeth. By the inward shift, edge pressure (R > ~1.50m) begins to decrease by the increase of plasma-wall interaction at the high field side, but core pressure increases linearly indicating ITB formation. Decrease in radiation power, decrease in D$_\alpha$ level, fast increase in the stored energy occur. As the β_N increases, the low frequency tearing mode is destabilized (~0.63s at R = 1.50m). The effect of the mode extends from the ETB region (~0.9a) to the ITB region (~0.3a) at 0.64s. The outward shift (~0.65s) terminates the ITB at the timing of the occurrence of the sawtooth. In this case, high β_N state was not maintained long in contrast to the previous low shear sawteeth-free case. It seems that m = 1 mode (sawteeth) and m = 2 mode (tearing mode) both exert effects to cause the destruction of the ITB.

2.2 Study of MHD at the edge transport barrier(ETB)

2.2.1 Radial electric field and quasi-coherent MHD oscillation measured by HIBP

In the course of obtaining high beta, the MHD stability of the ETB,which has steep gradient in pressure, is important. The structure of the negative electric field in the ETB was studied with CXRS (charge exchange recombination spectroscopy) diagnostics [3] and with HIBP (heavy ion beam probe) diagnostics [4] in JFT-2M.

We were aware that there are several grades in ETB strength, weak to strong, which was measured by the edge gradients and deuterium line radiation (D$_\alpha$) level [5]. ELM-free phase has the most strong ETB. We alredy found a

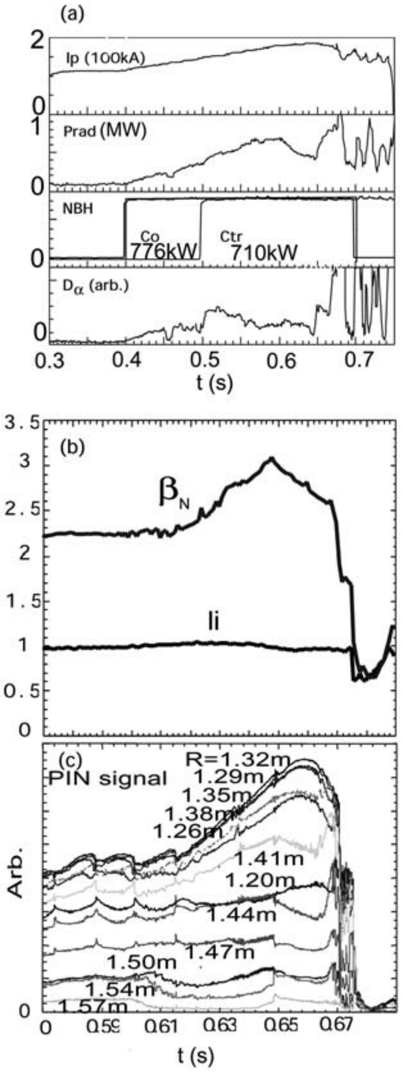

Fig. 2 (a) Time evolutions with sawteeth (NBH Co. 776kW than Ctr. 710kW).
(b) Time evolutions of β_N and inductance l_i.
(c) Time evolution of the Soft X-ray by PIN. *R* = 1.32m (center), *R* = 1.57m (edge).

slightly weaker ETB, called as H’ phase, which is characterized by a characteristic quasi-coherent density fluctuation with the frequency of ~100kHz measured by a microwave reflectometer with increased D_α level [6].

Figure 3 shows the profiles of the plasma potential (ϕ) measured by the HIBP and the intensity of the secondary beam of the HIBP which has the information on density. We find that in the ELM-free phase, negative electric field at the ETB (–15kV/m) is stronger than that in the H’ phase (–8kV/m) and that, during the H’ phase, density fluctuation of frequency ~130kHz localizes in the ETB region.

We are aware that such frequency is close to the frequency of the density fluctuation of the ELM precursor (~160kHz to ~100kHz) observed in ELMy H-mode [7]. Though we can not identify the MHD, it seems that the MHD affects the radial electric field, ETB strength or triggering of the ELM events at ETB.

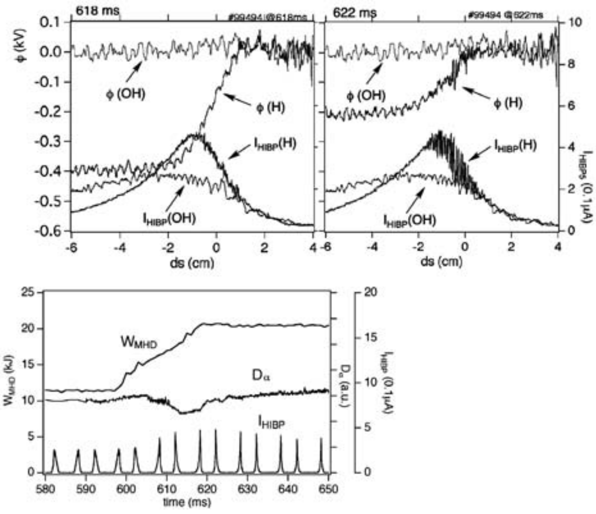

Fig. 3 Plasma potential profile and beam intensity profile of the HIBP measurement. ELM free H-mode (*t* = 618ms) and H′-mode (*t* = 622ms). d_s = 0 is the position of the separatrix. Minus represents the inside of the plasma and plus represents in the SOL. Density fluctuation at the ETB affects the I_{HIBP}.

2.2.2 Turbulent fluctuation and the quasi-coherent MHD oscillations in the ETB during the H′-mode and EDA-like mode

We observe quasi-coherent MHD oscillation in the ETB when the edge D_α intensity is comparatively large [8] as shown in Fig. 4(a). During the injection of NBH, we observe, successively, L-mode, ELM-free H-mode, H’-mode and EDA [9]-like mode (Fig. 4). Fig. 4(a) shows the density fluctuation spectrum at n_e~1.8×10^{19}m^{-3} (in the ETB) measured by the 38GHz microwave reflectometer [10]. The turbulent density fluctuation spectrum extends to ~100kHz during L-mode, but decreases to ~20kHz (with ~200kHz component) during the ELM-free H-mode. The quasi-coherent density fluctuation appears during the H’-mode. The frequency downshift occurs from ~110kHz to ~70kHz during this phase with its width Δf~20kHz. During this H’-mode, another quasi-coherent fluctuation ~300kHz [11] appears in the magnetic probe signal. As the density fluctuation in the ETB has not this 300kHz high frequency component (as in Fig. 4(a)) and reciprocating electrostatic probe measurement [8] detects the 300kHz oscillation in the SOL (scrape-off layer) region, the magnetic fluctuation seems to originate around the separatrix region to the SOL plasma region and not deep in the pedestal. In the EDA-like mode, the background turbulent density fluctuation spectrum widely extends to ~120kHz as in the L-mode, but low frequency part of the spectrum still much smaller than the L-mode. The ~300kHz quasi-coherent magnetic fluctuation has Δf~60kHz and wider than the quasi-coherent mode with ~70kHz in the H’ phase.

Figure 4(b) shows the power spectra which shows the quasi-coherent mode and turbulent density fluctuation in the L-mode phase, ELM-free H-mode phase, H’ phase and EDA-like phase. The L-mode phase has turbulent density

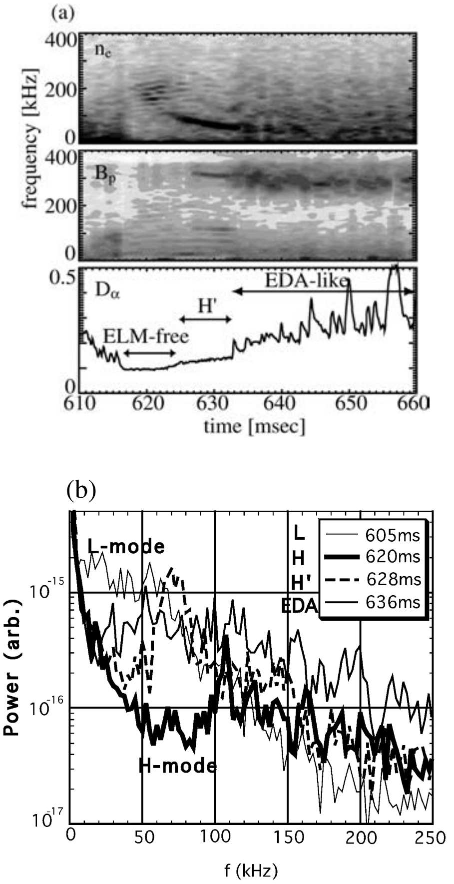

Fig. 4 Quasi-coherent mode observed in the edge transport barrier.
(a) density fluctuation spectrum measured by 38GHz reflectometer, spectrum of magnetic probe and D_α intensity during the H-mode.
(b) power spectrum of the density fluctuations at L-phase, H-phase, H'-phase and EDA-like phase.

fluctuation with half width ~70kHz. In the ELM-free H-mode phase, turbulent density fluctuation below 120kHz is suppressed to ~1/10. The half width of the background turbulence is 10~20kHz. In the H' phase, turbulence below 70kHz is suppressed and the quasi-coherent mode has $\delta f/f$ = 20kHz/70kHz. In the EDA-like phase, turbulence below ~40kHz is suppressed, though turbulence above 100kHz is enhanced. We point out that the fluctuation induced particle flux measured by the HIBP is also dominated by ~40kHz component during the L-mode [12].

Therefore it is plausible that the suppression of the turbulence below ~40kHz brings the significant confinement improvement during the EDA-like mode.

From these observation, following speculation may be derived. If we assume that the measured density fluctuation at n_e~1.8×10^{19}m^{-3} contributes mainly to the global particle/energy transport, the improvement of the transport during the ELM-free H-mode compared to the L-mode is due to the decrease in the background turbulence level (<100kHz). During the H'-phase, slightly enhanced transport than that in ELMfree case is due to the quasi-coherent ~100kHz fluctuation. In the EDA-like-phase, the enhanced transport compared to the ELMfree H-mode may due to the enhanced background turbulence level (>10kHz). But as the turbulence below ~40kHz is still suppressed compared to the L-mode, EDA-like phase still has improved confinement compared to the L-mode which indicates that low frequency part (<~50kHz) plays the dominant role for the transport in these JFT-2M conditions.

The role of the ~300kHz magnetic fluctuation around the SOL is not clear yet. We only point a possibility that a three wave coupling (geodesic electron acoustic mode, Alfven wave, low frequency quasi-coherent mode ~100kHz) enhances the transport [13].

3. Discussion on the relation to the "quasi-coherent mode" observed during EDA mode in the Alcator C-Mod tokamak

The "quasi-coherent mode" observed in the Alcator C-Mod tokamak has frequency of f = ~100kHz and $\Delta f/f$~0.05 to 0.2 [14]. In our "coherent mode" has f = ~110– ~70kHz and $\Delta f/f$ = ~0.2. In this respect, these two modes are quite similar. These two modes exhibit the frequency downshift presumably by decrease in edge plasma rotation. The radial electric field measured by HIBP is –8kV/m in our case is 1/3 of their BOUT calculation for C-Mod. The "quasi-coherent mode" is considered as a form of resistive ballooning mode known as the resistive X-point mode. We observe the high frequency mode (~300kHz) in magnetic field and low frequency mode (~100kHz) in density fluctuation at the same time. It may be the next task to measure the MHD over 1MHz to detect Alfven wave etc.

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