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MHD Stability of Plasmas with Edge Pressure Pedestal in the Large Helical Device

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1. Introduction

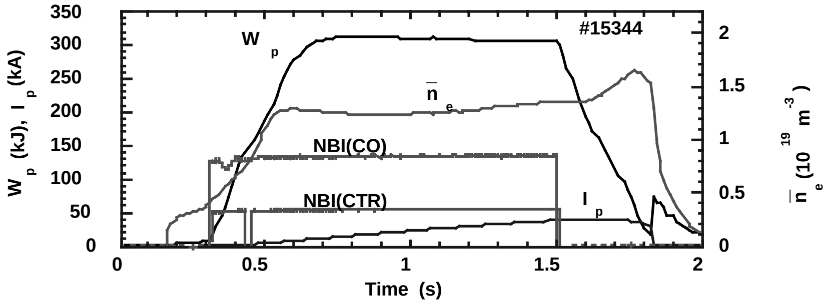
Clear temperature or pressure pedestal near the plasma edge is often observed in inward-shifted plasmas heated by neutral beam injection (NBI) on the Large Helical Device (LHD)[1]. This pedestal formation contributes to improve the global plasma confinement[2]. It is important to clarify the MHD stability near the plasma edge against pressure driven MHD instabilities such as interchange modes and the effect of these instabilities on the pressure profile near the edge. This study would contribute to find a way for simultaneous achievement of high plasma beta and improved plasma confinement.

This paper is devoted itself to discussing the characteristics of MHD instabilities excited near the plasma edge in neutral-beam-injection (NBI) heated plasmas. In the experimental studies, NBI power (P_{NBI}) are injected up to 4 MW at toroidal fields Bt = 2.75 T and 1.5 T, where the magnetic axis position of the vacuum field is mostly Rax=3.6 m and sometimes Rax=3.75 m. MHD fluctuations are monitored with 8 sets of three-axial magnetic probes (MPs) arranged helically inside the vacuum vessel[3] and two sets of magnetic probes placed on the top ports of the LHD by 108 degrees away in the toroidal direction[4]. Two sets of a 40-channel soft X-ray (SX-) detector array are also arranged by 108 degrees away in the toroidal direction to measure the internal structures of the MHD modes[4, 5].

2. MHD fluctuations excited near the plasma edge

In NBI heated plasmas, low frequency magnetic fluctuations less than 3 kHz are often observed, accompanying several satellites. Typical time evolution of magnetic fluctuations is shown in Fig.1, together with those of the plasma stored energy, line avearaged electron density and net plasma current, where Bt = 2.75 T, Rax = 3.6 m, P_{NBI} ~ 2.6 MW and the averaged plasma beta value < $_t$> =0.15 – 0.4 %. In this shot, the central electron temperature reaches about 3 keV and the temperature at the 1/q=1 surface (~ 0.9) is about 1.1keV. As seen from the contour plot of magnetic fluctuations vs frequency and time (Fig.1(b)), the frequency of the fundamental mode f_o similarly evolves to the time trace of the stored energy Wp[4]. The satellite modes having the frequency $2f_o$ and $3\ f_o$ are clearly seen in the magnetic fluctuations. However, only the fundamental mode is identified in the SX-fluctuations, while high coherence between SX-signal and MP-signal is also seen at f~ $2f_o$. This might be due to the strong path integral effect in SX-signals for the higher harmonics with higher poloidal mode number. The toroidal mode number of the fundamental mode is determined to be n=3 from the analysis of two magnetic probes placed in the toroidal direction. The phase relation among SX- fluctuation signals clearly indicates the odd poloidal mode(Fig.2). Moreover, a simple simulation where the island structure with the poloidal mode number m in the SX-emission profile is rotating as a rigid body also indicates to be m=3[5]. As seen from Fig.2, the soft X-ray fluctuation amplitude - Isx rapidly rises near the edge and reaches the peak just inside the edge. If the path integral effect in the soft

(a)



(b)

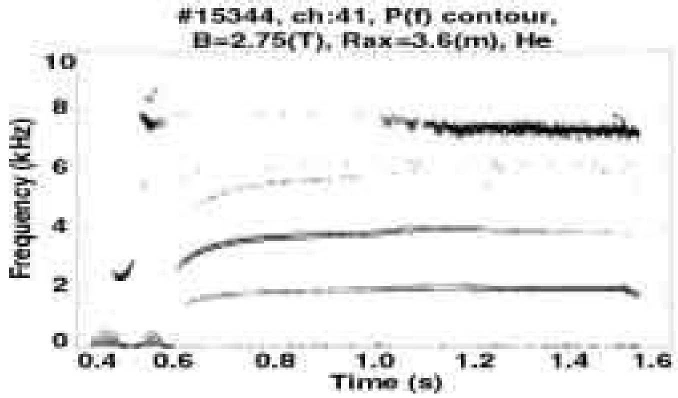


Fig.1(a) Time evolutions of Wp, line averaged electron density and net plasma current in an NBI heated high temperature plasma, (b)magnetic fluctuation amplitude vs frequency and time.

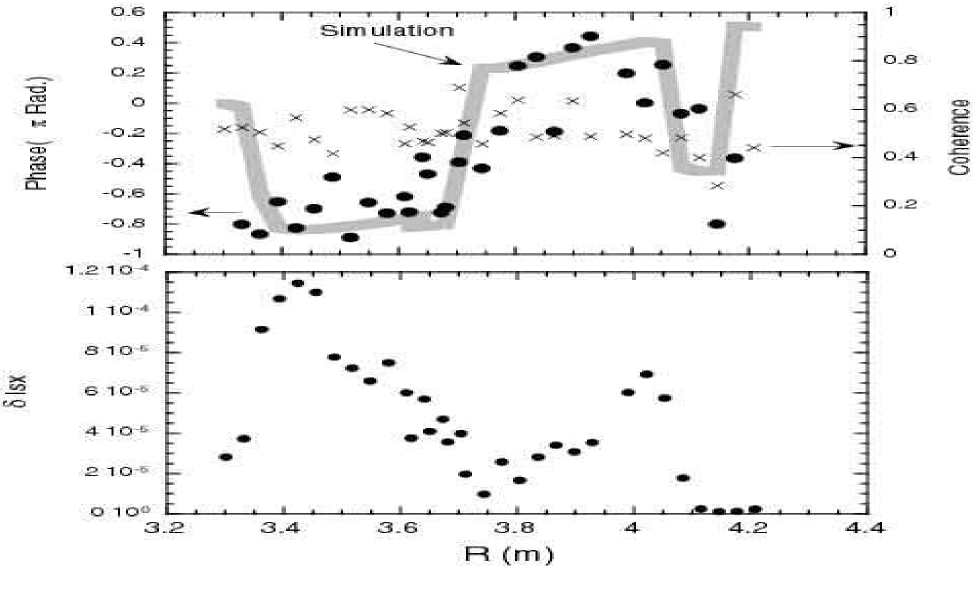


Fig.2 Coherence and phase between SX-signals and MP-signal, and SX-fluctuation amplitude Isx as function of the major radius. The bold curve in the top figure indicates the phase behaviour for the m=3 mode calculated by the simulation.

X-ray signal is taken into account, the fluctuations localize near the edge (at R ~ 4.1m or at ~ 0.9) around the rational surface 1/q=1. This is also consistent with the experimentally obtained mode numbers, m=3/n=3. The island width is inferred to be w/<a> ~ 0.05. In some shots, the satellites up to fifth harmonic are identified. The fundamental mode and the satellites propagate in the ion diamagnetic drift direction in the laboratory frame. Note that the modes localized near the edge are thought to be resistive interchange modes because the edge region is stable against ideal interchange modes. As seen from Fig.1(b), the other type of magnetic fluctuations of about 7 kHz is identified as m=2/n=1 mode in the latter half of the discharge where an appreciable amount of the net plasma current is induced. This mode is destabilized when < $_t$> exceeds about 0.3 % and the net plasma current reaches a certain threshold. Note that this mode propagates in the electron diamagnetic drift direction in the laboratory frame. It is predicted that the m=2/n=1 mode localizes around 1/q=1/2 rational surface in the plasma core region (~ 0.5) and presumably is ideal interchange mode. Dependence of the frequency and amplitude of the m=3/n=3 mode localized in the edge region on < $_t$> is shown in Fig.3. The m=2/n=2 mode observed at the low toroidal field (Bt=1.5T) and Rax=3.75 m is also plotted in this figure. The magnetic fluctuation amplitude is in the range of 1 to 3 x 10^{-6} T at the magnetic probe position which is considerably outside the last closed flux surface (LCFS), that is, at ~ 3. The magnetic fluctuation amplitude of m=3/n=3 or m=2/n=2 mode is estimated to reach about 0.5-1 x 10^{-4} T at LCFS. The frequency is increased with the increase in Wp and tends to saturate. The frequency agrees well with the ion diamagnetic drift frequency estimated by the electron temperature at the 1/q=1 surface. It is consistent with the fact that the measured radial electric field around the 1/q=1 surface is fairly small in these plasmas obtained in this experimental campaign where the line averaged electron density is in the range of 1 – 2 x10^{19}m^{-3}. Therefore, the frequency of the MHD mode localized at 1/q=1 surface approximately reflects the magnitude of the pressure gradient at the 1/q=1 rational surface.

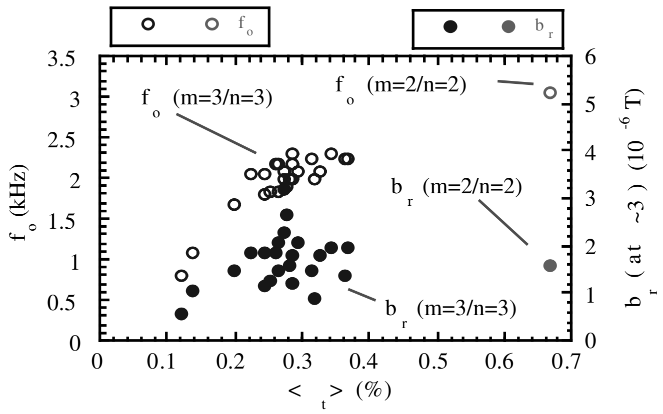


Fig. 3 Frequency and magnetic fluctuation amplitude of the fundamental mode as a Function of < $_t$>.

3. Effects of MHD modes on plasma pressure profile near the edge

It is interesting how the appreciable growth of the observed MHD modes localized near the edge affects the pressure profile. In the plasma heated by 1.8 MW NBI at low Bt (=1.52T), the m=2/n=2 MHD modes were suddenly enhanced, as shown in Fig.4. The amplitude of the fluctuations weakly destabilized at about 0.80 s are suddenly enhanced by a factor three at 0.87 s with the growing time of $_g$~ 1 ms and quickly saturates within about 2 ms. In this phase, the mode frequency is also suddenly reduced by about 25 %. The modes appreciably modify the soft X-ray emission profile, suggesting the flattening of the pressure profile around the 1/q=1 rational surface(Fig.4). This process leads to the rapid saturation of the mode amplitude.

Relaxation oscillations were observed in edge SX-signals when the edge pressure gradient was transiently increased by hydrogen ice pellet injection (till t ~ 0.91s) during high power NBI heating, where Bt=1.5T and P_{NBI} = 3.9 MW (Fig.5). The oscillations seen in 1.0 < t < 1.2 s of Fig.5 correlate well with H -emission spikes and magnetic fluctuation bursts. They are similar to the edge localized modes (ELMs) observed in a tokamak H-mode. However, it is not clear what rational surfaces near the edge play an important role in inducing the ELM like activities.

4. Summary

Pressure driven m=3/n=3 and m=2/n=2 MHD modes and their satellites to fifth harmonic were observed in NBI heated plasmas where the pressure pedestal or steep pressure gradient are clearly formed near the edge. These modes are localized around the 1/q=1 rational surface which is located near the edge (~0.9). When these modes rapidly grows beyond a certain level, they reduces the pressure gradient at the relevant rational surface. This process quickly suppresses the exponential growth of these modes and then leads to the sudden saturation. This process was clearly seen in LHD plasmas. In pellet fueled discharges at low Bt=1.5 T, ELM like relaxation oscillations were observed in SX-signals. So far, the relative change in SX-emission due to these oscillations is fairly small. The nonlinear evolution of pressure-driven modes is one of important issues related to MHD stability in a helical plasma and will be paid much attention in the next experimental campaign.

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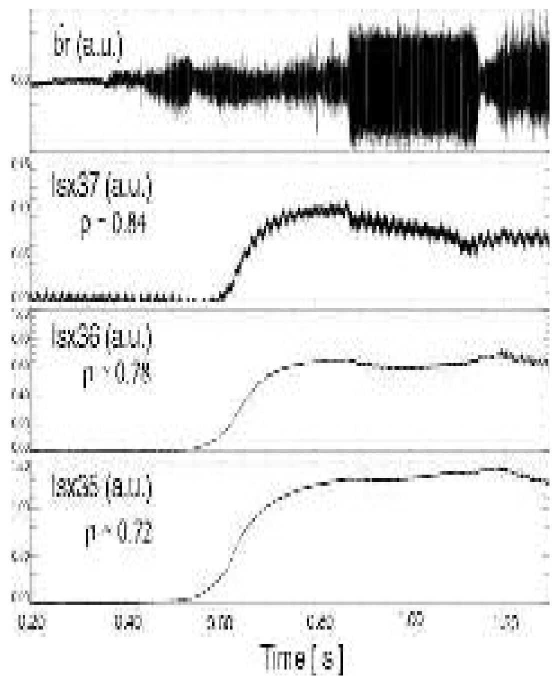

Fig.4 Time evolutions of m=2/n=2 magnetic fluctuations and SX-signals near the plasma edge, where Bt=1.5 T and Rax=3.75 m. The top SX-emission (ISX37) is radiated from the edge and bottom one from more interior.

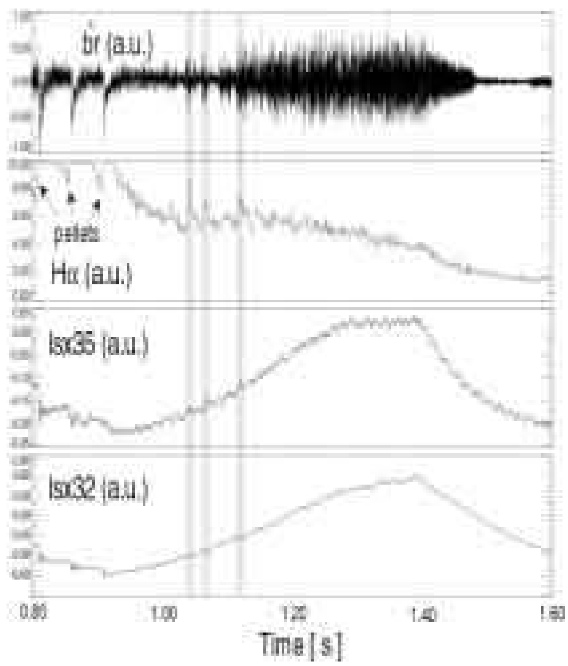

Fig.5 Time evolution of MP-signal, H emission and SX-signals near the edge in the shot with ELM like activities, where Bt=1.5 T and Rax =3.6 m. A few ELM like activities are indicated by the vertical gray zone.