Ballooning Structure of Edge MHD Mode Observed in the Large Helical Device Plasmas with Externally Applied Magnetic Perturbations

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In the vacuum magnetic configuration of the Large Helical Device (LHD), the last closed flux surface (LCFS) is always surrounded by the ergodic layer [1]. In high beta (=plasma pressure/toroidal magnetic pressure) and/or L-H transition discharges of LHD, resistive interchange modes having lower mode numbers, i.e. m/n = 1/1, 1/2, 2/3, 3/4 and 3/5 (m, n: poloidal and toroidal mode numbers) are easily excited by steepening the pressure gradient in the ergodic region, because the region is characterized by high magnetic shear but the magnetic hill [2-5]. Figure 1 shows a typical example of the radial profile of Soft X-ray (SX) fluctuations of the m/n = 2/3 edge MHD mode observed in an L-H transition plasma on LHD and compares it with the simulation result based on a simple perturbation model of interchange mode. They agree very well each other and also for the m/n = 1/2 mode. The observed radial profile obviously indicates the character of interchange mode that the fluctuation amplitudes at inboard (smaller major-radius) and outboard (larger major-radius) sides of the torus are almost same.

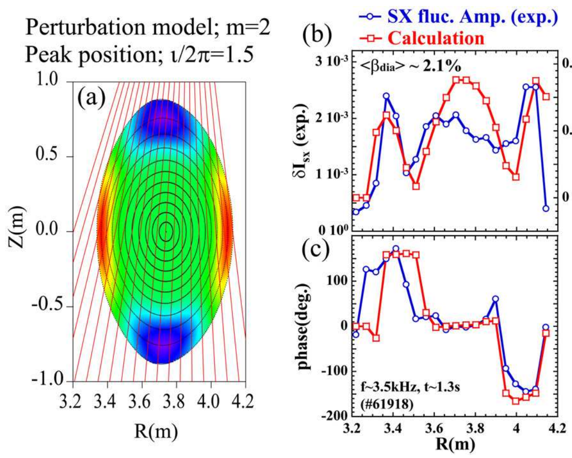

Fig. 1 Comparison of radial profile of SX fluctuation amplitudes of the m/n = 2/3 mode between experimental observation and a simple perturbation model; (a) perturbation model and sight lines of an SX array, (b, c) experimentally obtained radial profiles of SX fluctuation amplitude and phase difference of the m/n = 2/3 mode as a function of the SX sight lines.

In LHD, a pair of perturbation field coils is installed on upper and lower port areas in 10 vertically elongated sections, of which coil set is called the Local Island Divertor (LID) coils and are able to generate resonant helical perturbation field of the m/n = 1/1. Recently, effects of a sizable m/n = 1/1 static island generated by the perturbation field on these edge MHD modes have been investigated [6].

Figure 2 shows a discharge waveform of an NBI heated L-mode plasma with the large perturbation field (I_{LID} / B_{t} =1111A/T; I_{LID} is the LID coil current, B_{t} is the toroidal field strength). The volume-averaged beta value is obviously deteriorated by the perturbation field, compared to a plasma without it. In the discharge, the m/n = 3/4 mode dominates magnetic fluctuations. Just after switch-on of an additional NBI (t > 2.8 [s]), the m/n = 2/3 mode is also enhanced. However, the m/n = 1/2 mode which has often large amplitude magnetic fluctuations in L-H transition plasmas at lower toroidal magnetic field ($|B_{\mathrm{t}}| \leq 0.9$ [T]) was not observed. Figure 3 shows the electron pressure profiles (P_{e}) obtained by Thomson scattering measurements and the Poincare plots of the vacuum magnetic field in the horizontally elongated section at I_{LID} / B_{t} =1111A/T. As shown in Fig. 3(a), formation of a sizable m/n = 1/1 static island is recognized by the flattening of the electron pressure, where a vacuum m/n = 1/1 static island width normalized by a minor radius is approximately 20[%] in Fig. 3(b). The edge electron pressure gradient outside of the m/n = 1/1 static island remains unchanged even by the island formation, regardless of the significant decrease in the core electron pressure. It should be noted that the outside of the sizable m/n = 1/1 static island is strongly ergodized in the vacuum field (Fig. 3(b)). As shown in Fig. 2(b), the rational surfaces of the m/n = 3/4 and 2/3 modes having large amplitude are located in the region of the steep pressure gradient outside the m/n = 1/1 static island.

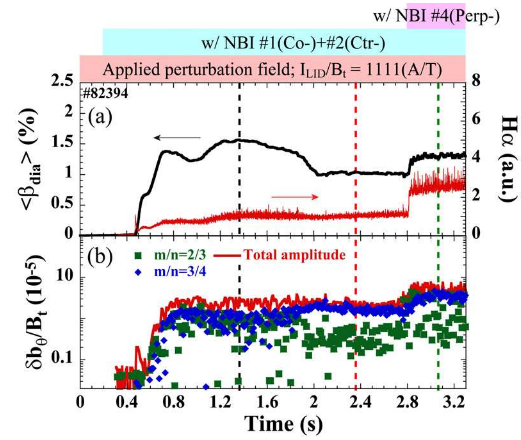

Fig. 2 Time evolution of an L-mode plasma with the applied large perturbation field. (a) Volume-averaged beta and Hα signal. (b) Magnetic fluctuation amplitudes related to the edge MHD modes.

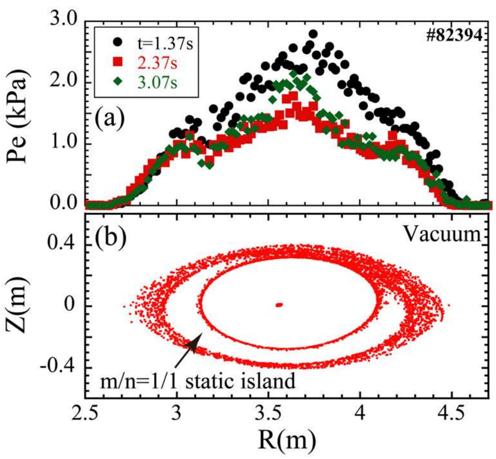

Fig. 3 (a) Electron pressure profiles of a discharge shown in Fig.2 obtained by Thomson scattering measurements. (b) Calculated Poincare plots of the vacuum field in the horizontally elongated cross section with I_{LID} / B_{t} =1111A/T.

In order to investigate the radial structure of edge MHD modes, we have carried out simultaneous measurements using SX arrays at two different vertically elongated sections by 108 degrees away in the toroidal direction. Three sets of SX arrays of which array consist of 20-channel PIN photodiodes are employed. Their sight lines are shown in Figs. 4(a) and 4(b) together with calculated Poincare plots of the m/n = 1/1 static island. In Figs. 4(c) and 4(d), the radial profiles of the SX intensity (I_{sx}) and its fluctuation amplitude (δI_{sx}) for the m/n = 2/3 and 3/4 edge MHD modes are shown, where triangle (inverted triangle) symbol indicates the data just before (during) the additional NBI in a shot shown in Fig. 2. As seen from Figs. 4(c) and 4(d), the δI_{sx} is increased more asymmetrically by the additional NBI heating from t = 2.8[s]. Especially, that on the outboard side at the 6.5U port increases remarkably, while that in inboard side increases slightly. On the other hand, that on the inboard side at the 3.5U port increases appreciably, although that in the outboard side hardly changes. The asymmetric evolutions of the δI_{sx} profiles are obviously different from the character of the interchange mode as shown in Fig. 1. We try to explain the observed asymmetric structures in these SX fluctuation amplitudes, using a simple model where the edge MHD mode amplitude is dominantly enhanced at the localized zone just outside the O-point of the m/n = 1/1 sizable static island. This model is schematically drawn in Fig. 4(e). As seen from Figs. 4(b) and 4(d), the δI_{sx} at the 6.5U port is strongly enhanced near the O-point of the m/n = 1/1 static island. The feature of the δI_{sx} profile at the 3.5U port is also consistently explained by Figs. 4(a) and 4(c).

From stability analyses based on fixed and free boundary MHD equilibria on LHD, a possibility of ballooning mode has been shown in high beta plasmas with $\beta \geq 3$[%] [7]. Two types of ballooning modes depending on Mercier stability can exist in the LHD configuration. One is the tokamak-like ballooning mode which is mostly excited in a plasma with large Shafranov shift and is excited through weak toroidal mode coupling. The intermediate toroidal mode number $n \sim N = 10$ is expected, where N is the toroidal period number ($N = 10$ for LHD). The other is the ballooning mode excited through strong toroidal mode coupling, which has larger toroidal mode number $n >> N$. On the other hand, the magnetic configuration in our experiments is considerably different from a usual LHD configuration discussed in the above-mentioned theoretical analyses. In our experimental results, there is a possibility that the large m/n = 1/1 perturbation field will tend to decrease $N = 10$ to $N \sim 1$. Under the situation, the observed n = 3 and 4 modes might be a ballooning type mode corresponding to the former case, which are excited by the steep edge pressure gradient near the O-point of the m/n = 1/1 static island. This seems to be similar to the tokamak-like ballooning modes excited by m/n = 1/1 rotating island on TFTR tokamak [8]. However, the possibility of an interchange type mode deformed by the formation of the m/n = 1/1 static island cannot be ruled out so far. The above discussion should be improved by both experimental and theoretical approaches to draw the definite conclusion.

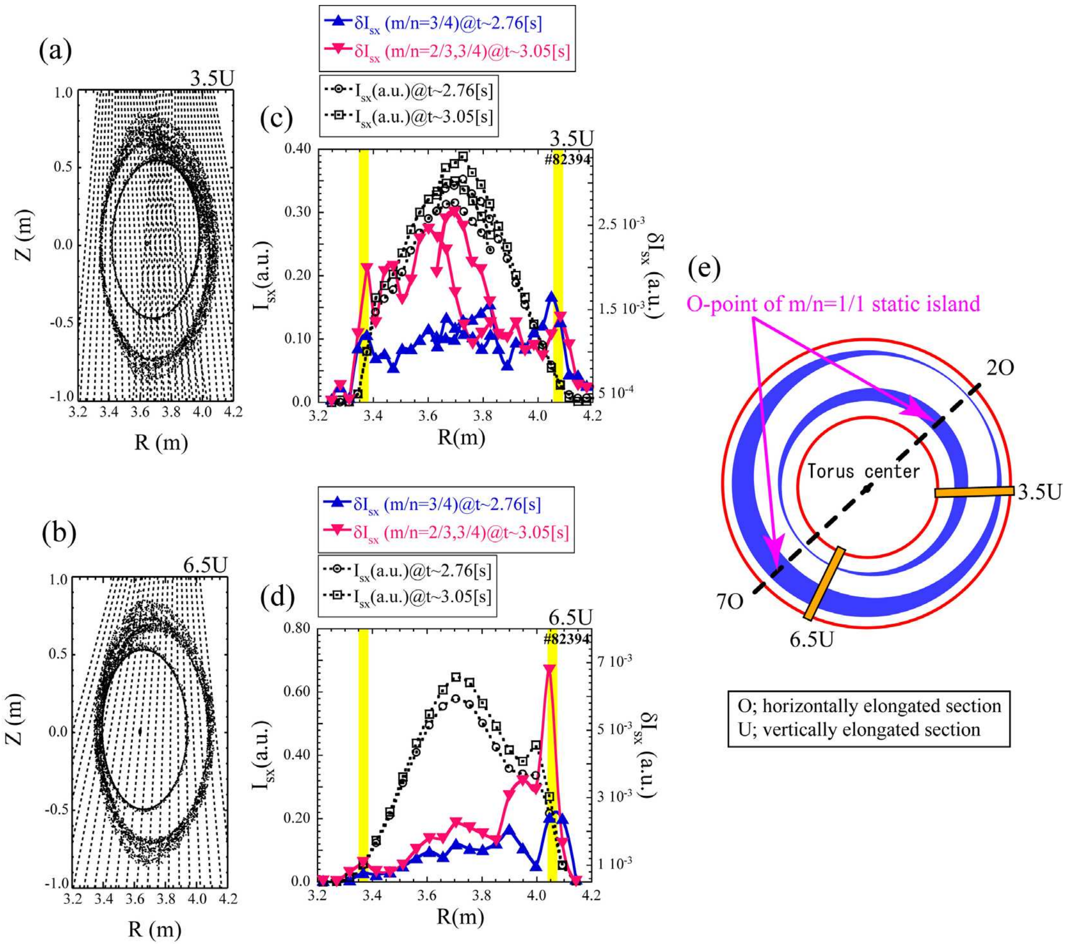

Fig. 4 (a, b) Calculated m/n = 1/1 static island and overlaid lines of sight of the SX arrays in different observation sections (3.5U and 6.5U ports). (c, d) Radial profiles of SX intensity (I_{sx}) and SX fluctuation amplitude (δI_{sx}) of the edge MHD modes in a shot shown in Fig. 2, where the shaded zone indicates the inferred m/n = 3/4 rational surface. (e) Schematic top view of the LHD torus in the equatorial plane (z = 0). Crescent zones indicate the expected width of the m/n = 1/1 static island.

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