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Pressure Driven MHD Instabilities Observed in Neutral Beam Heated Plasmas of the Large Helical Device

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Abstract

Two types of low frequency (< 10 kHz) magnetohydrodynamic (MHD) instabilities are observed with the magnetic probes in neutral beam heated plasmas of the Large Helical Device (LHD). One has m = 3 / n = 3 mode structure and the frequency increases with the increase in the bulk plasma beta and tends to saturate. This mode generates the second and third harmonics. The other is m = 2 / n = 1 mode and seems to be excited when the plasma beta value exceed the threshold (~ 0.3 %) and the plasma current reaches a certain level. The radial structure of soft X-ray fluctuations suggests that the former mode is excited near the edge. The former mode is considered to be the resistive interchange mode excited in the plasma edge region around the 1/q = 1 surface and the latter is the ideal interchange mode excited in the plasma core region around the 1/q = 0.5 surface.

Keywords:

MHD-activity, magnetic fluctuation, Soft X-ray fluctuation, rotational transform, rational surface, magnetic shear

1. Introduction

An important challenge in nuclear fusion research is to sustain a high performance plasma in steady state. Extensive efforts toward this challenge are being made in many large tokamaks. However, improved confinement discharges in a tokamak are often terminated by current driven MHD instabilities close to the MHD stability boundary (see e.g. [1]). On the other hand, a helical device is thought to be of great advantage to sustain the plasma in steady state without harmful current disruption. In helical devices, however, pressure driven MHD instabilities such as ideal/resistive interchange modes and ballooning mode are predicted to be most dangerous for sustainment of high performance plasmas. For steady-state sustainment of helical plasmas, it is very important to stabilize these MHD instabilities. In the Compact Helical System (CHS), which is a small sized heliotron/torsatron, ideal/resistive interchange modes with low mode numbers such as m / n = 2 / 1 are detected using magnetic probe arrays, where m and n are poloidal and toroidal mode number, respectively [2]. Recently, energetic ion driven modes, toroidicity induced Alfvén eigenmodes and "fishbone-like burst modes" are also observed in CHS [3,4].

In the Large Helical Device (LHD) which is a larger version of CHS, both pressure driven and energetic-ion-driven MHD instabilities are observed during high power neutral beam injection (NBI). This paper focuses on the former instabilities in LHD and latter ones are discussed in the other paper [5].

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2. Experimental Setup

In order to detect MHD fluctuations in the LHD plasma, we installed two sets of soft X-ray detector array (SX-array) and magnetic probe array which are arranged by 108 degrees away in the toroidal direction (Fig. 1). The magnetic probe array consists of two probes for measurement of radial and poloidal magnetic fluctuations. Each probe is made of a boron-nitride bobbin and stainless steel wire, so that the outgassing rate should be minimized. The resonance frequency of the probe with ~2 m connection coaxial cable is about 1 MHz. Poloidal magnetic field fluctuations measured by the probes are very small, because the magnetic probe arrays are placed in the vertically elongated port section where the poloidal field fluctuations are much reduced by the resistive wall area of the port section. In this experiment, therefore, we usually analyze the radial magnetic field fluctuation. The internal mode structure of the fluctuations is obtained from a 40-channel SX-array with 15 μm beryllium filter. The magnetic probes and soft X-ray detectors can detect the fluctuations up to 500 kHz and 200 kHz, respectively. These signals are converted into digital data with sampling rate of 100 kHz. We also use eight Mirnov coils which are placed on the vacuum vessel wall every 10 to 20 degrees in the poloidal direction along the helical coil of LHD. The Mirnov coils are employed to determine the mode numbers. In this paper, we call this probes "helically arranged magnetic probe array".

High performance discharges of LHD are obtained in the inward shifted magnetic axis position of the vacuum field (R_{ax} = 3.6 m) at high toroidal magnetic field (B_t ~ 2.8–2.9 T). We analyze MHD fluctuations in these types of plasmas, where they are heated by balanced NBI, electron cyclotron waves (ECW) and short pulse (< 0.3 s) ion cyclotron waves (ICW). The total heating power is 3–5 MW. The stored energy, line averaged electron density and plasma current are in the range of W_p = 150–450 kJ, $\bar{n}_e \sim 1\text{–}2 \times 10^{19}$ m^{-3} and I_p = 0–50 kA, respectively. The central electron temperature $T_e(0)$ reaches 3 ~ 3.5 keV. The signals of the SX-array reflect mainly electron density, because the cut off energy of the bellylium filter is about 1.3 keV.

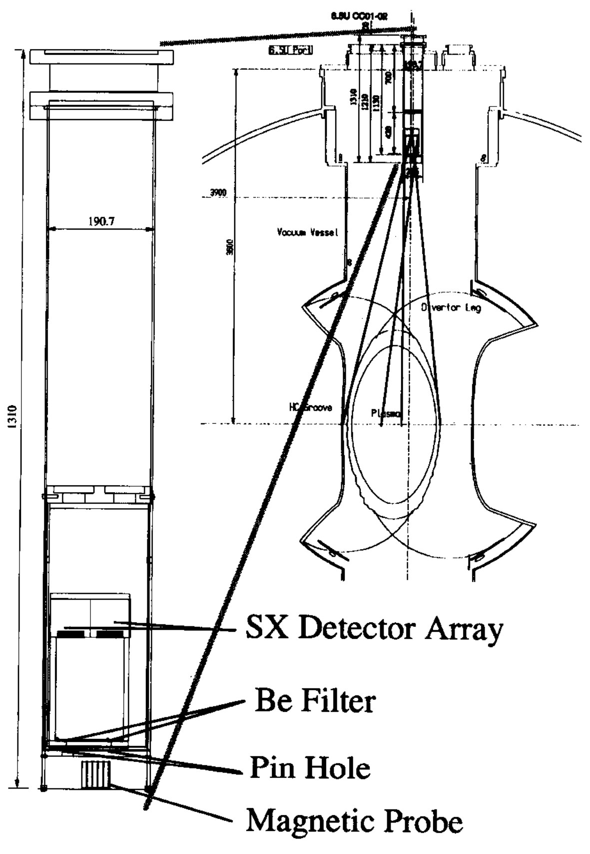

Fig. 1 The Schematic drawing of soft X-ray detector array (SX-array) and magnetic probe array.

3. Experimental Results

Typical time evolution of the magnetic fluctuations in a helium plasma heated by NBI, ECW and ICW is shown in Fig. 2, where the magnetic axis position of the vacuum field is R_{ax} = 3.6 m, B_t = 2.75 T and total absorbed power reaches about 5 MW. In this experimental campaign, the averaged plasma beta value measured by a diamagnetic loop is relatively low, that is, β = 0.2–0.4 %. The electron temperature profile measured with Thomson scattering has a triangle shape having edge pedestal. On the other hand, the profile of the electron density is hollow. The pressure profile is not very peaked, that is, slightly broader than a parabolic shape. As seen from Fig. 2, three coherent modes with very narrow spectral width are identified. The mode frequencies evolve in time, exhibiting the similar time trace of the stored energy. The modes having the frequencies which are just two and three times higher than the lowest frequency f_0 are thought to be the satellites of the mode with f_0. The mode frequency is shown in Fig. 3 as a function of the stored energy for various shots obtained in this campaign. The toroidal mode number of the lowest frequency mode is determined to be n = 3. The poloidal mode number is predicted to be m = 3 from the helically arranged magnetic probe array. Derivation of poloidal mode number is fairly difficult and somewhat uncertain,

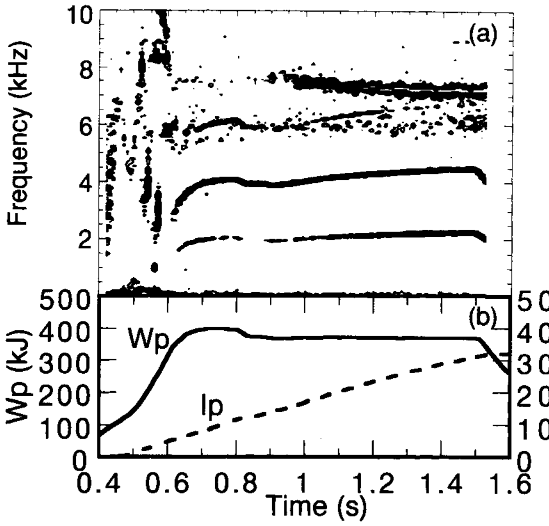

Fig. 2 (a) Typical time evolution of the magnetic fluctuations in a helium plasma of LHD, where NBI, ECW and ICW are applied at 0.3–1.5 s, 0.6–1.7 s and 0.6–0.9 s, respectively. (b) Time evolution of the stored energy and net plasma current.

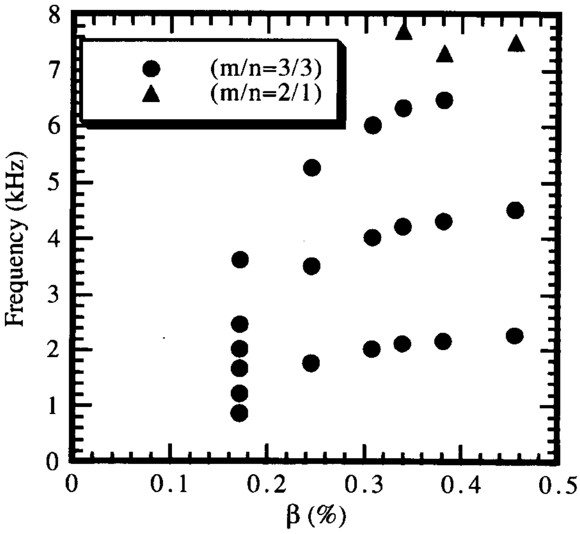

Fig. 3 Dependence of the frequencies of the observed magnetic fluctuations on the average plasma beta value.

because the phase difference between each adjacent probe is not smoothly changed. These three modes rotate in the direction of ion diamagnetic drift.

The internal structure of the lowest frequency mode was measured with the SX-array. Fig. 4 (a) shows the radial profiles of soft X-ray fluctuations related to the lowest frequency mode ($f \sim 2$ kHz) observed in the shot

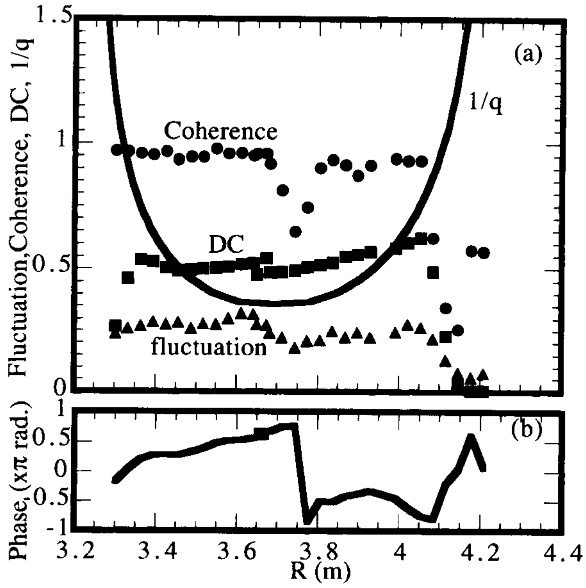

Fig. 4 (a) Radial profiles of soft X-ray fluctuations S1 and the coherence between the soft X-ray signal of each channel and the magnetic probe signal for the mode of frequency $f \sim$ 2kHz observed in the shot of Fig. 2. (b) Radial profile of the phase between the soft X-ray signal of each channel and the magnetic probe signal.

of Fig. 2. The coherence between the soft X-ray signal of each channel and the magnetic probe signal calculated in the relevant frequency range are also plotted. This figure suggests that the fluctuation level and coherence rise from last closed flux surface to the maximum at $\rho \approx 0.8$ ($R \sim 4.07$ m), where ρ is the normalized plasma minor radius. If the path integral effect along the line of sight in the SX-signal is taken into account, the above mentioned radial profile of fluctuation amplitude and coherence suggest that the instabilities are localized around $\rho \sim 0.9$ of which position corresponds to the $1 / q = 1$ rational surface. The profile of the phase indicates that the poloidal mode number is odd (Fig. 4 (b)). This result is consistent with the result from magnetic probes, that is, m = 3. That is, the lowest frequency mode has m = 3 / n = 3 structure.

If the mode is situated near the edge, the mode frequency may be affected by the condition of peripheral plasma region. In Fig. 5, the frequencies of the modes step up at about $t = 0.9$ s. No change in global plasma parameters such as the stored energy and line averaged density is observed at this moment. However, it is predicted from the change of SX-intensity profile that only the gradient of the plasma pressure in

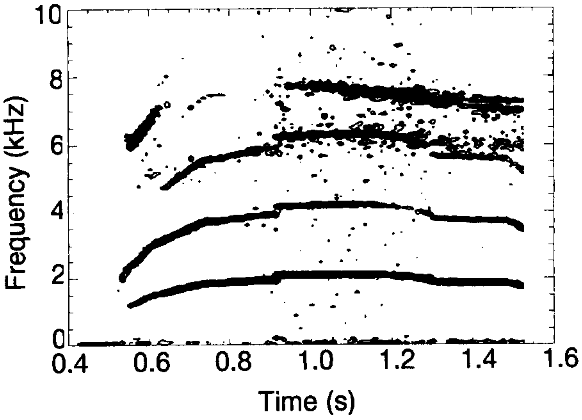

Fig. 5 Time evolution of the frequencies of the magnetic fluctuations observed in a plasma where the plasma pressure gradient is suddenly changed at $t \sim 0.9$ s only in the edge region.

the peripheral region is suddenly changed. This change may lead to the change of the diamagnetic drift frequency or that of the radial electric field. This fact also suggests that the mode is situated in the peripheral region.

Even in the inward shifted configuration (R_{ax} = 3.6 m), the plasma edge region is predicted to be stable against Mercier mode in the present experimental condition. The plasma presented in this paper has steep pressure gradient near the edge around the 1 / q = 1 surface. Resistive interchange mode is thought to be a plausible candidate for these low frequency modes, because resistive effects still play an important role in the edge region.

In the plasma shown in Fig. 2, another mode of $f \sim$ 7 kHz is observed. The mode frequency tends to decrease, while the stored energy is kept constant in time. The mode seems to be excited when the average plasma beta value is larger than about 0.3 % (Fig. 3) and a small net plasma current is induced more than ~ 10 kA (Fig. 2). The poloidal and toroidal mode numbers are m = 2 and n = 1, respectively. The 1 / q = 1 / 2 rational surface is predicted to be at ρ = 0.3–0.5 in the shot. The modes possibly exist in the core region. It rotates in the direction of electron diamagnetic drift. This rotation direction might be affected by the Doppler effect due to a plasma rotation. Fluctuations of soft X-ray are not observed in spite of fairly large amplitude of the magnetic fluctuations. The fluctuation of soft X-ray emission $\tilde{S}$ is given as $\tilde{S} = \xi_r \cdot dS_0/dr$, where ξ_r is the radial plasma displacement and S_0 is the Soft X-ray emission intensity of the equilibrium profile. In the plasmas discussed in the paper, the profile of S_0 is almost flat in the core region of $\rho \leq 0.7$. Therefore, the fluctuation signal $\tilde{S}$ is strongly reduced due to very small dS_0/dr, even if ξ_r is fairly large. This is the reason why the soft X-ray fluctuations caused by m = 2 / n = 1 mode are not detected well above the noise to signal ratio in the SX-signals. The modes are observed on the condition that the plasma beta value exceed the threshold of about 0.3 % and the plasma current reaches a certain level. This can be explained as follows. That is, the increase in $\langle\beta\rangle$ and/or in the net plasma current in the co-direction tends to reduce the magnetic shear at the 1 / q = 1 / 2 rational surface, and then leads to destabilize m = 2 / n = 1 mode which is presumably ideal interchange mode.

4. Conclusion

We have observed two kinds of low frequency (< 10 kHz) MHD modes in NBI heated plasmas of LHD. The frequency of the modes, which are located near the edge around 1 / q = 1 surface, increases with the bulk plasma beta value and tends to saturate at the high plasma beta. The mode usually accompanies the second and third harmonics as satellite modes. The other mode, which is predicted to be in the plasma core region, is observed on the condition that the plasma beta value exceeds about 0.3 %. The former instability is considered to be the resistive interchange mode excited around the rational surface of 1 / q = 1 in the plasma peripheral region. The latter one is considered to be the ideal interchange mode excited around the 1 / q = 1 / 2 surface in the plasma core region.

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