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MAGNETIC FLUCTUATIONS IN L-MODE AND H-MODE ON THE JFT-2M TOKAMAK

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Magnetic fluctuations (2.5 kHz < f < 50 kHz) have been investigated by pick-up coils in a H-mode divertor discharge and a H-mode-like limiter discharge of the JFT-2M tokamak. A clear correlation between an L-to-H transition and a reduction of the fluctuation is obtained in both cases. The high frequency fluctuation (f > 10 kHz) enhanced by beam heating has been observed in the L-mode of a fully expanded limiter discharge.

Keywords: Magnetic Fluctuation, H-mode, L-mode, Tokamak, Divertor Discharge, Limiter Discharge

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ＪＦＴ－２Ｍトカマクにおけるしモードおよび Ｈモード時の磁場揺動

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ＪＦＴ－２Ｍにおける磁場揺動（2.5 kHz ＜50kHz）をＨモードとＬモードのプラズマについてピックアップコイルを用いて測定した。ダイバータ配位でもリミター配位でも，ＬモードからＨモードへの遷移に対応して磁場揺動の減少することが明確に観測された。真空容器内いっぱいにプラズマを作ったリミター配位のＬモードでは，周波数の高い揺動（f＞10 kHz）のうちビーム加熱によって振幅が大きくなるものの有ることが解った。

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1. INTRODUCTION

Many tokamaks have experienced deterioration of energy confinement with additional heating. Stored energy seems to increase offset-linearly as power increases. Some empirical scalings (L-mode scalings) are proposed for this phenomena[1][2]. Since these scalings are so pessimistic for a design of a fusion reactor, improvement and optimization of energy confinement in additionally heated plasma are necessary to achieve an ignition condition. The optimization of the confinement property is impossible without understanding physical mechanism of the deterioration in the L-mode. ASDEX is a first machine which had discovered experimentally an improved confinement mode, so called H-mode, with a closed divertor configuration[3]. Following ASDEX's experiments, PDX[4] with closed divertor and Doublet III[5] and PBX[6] with open divertor also obtained H-mode. Recently H-mode-like transition in a limiter discharge[7] was demonstrated on the JFT-2M tokamak. One of important facts observed in the above mentioned tokamaks is that particle confinement is much better in the H-mode than in the ohmic heating phase, and suggests that at least an anomalous transport which exists even in the ohmically heated plasma decreases in the H-mode. In spite of the successes to obtain improved confinement modes and some understandings of necessary conditions to obtain the H-mode transition in above mentioned tokamaks, physical mechanisms of the deterioration in the H-mode are still not well understood. A plasma with H-mode transitions is in an ideal situation to study the origin of the anomalous transport in the tokamak plasma, because quantities which behave in different manners between the H-mode and the L-mode must be important.

Magnetic fluctuation or diffusion of magnetic field line are proposed as one of candidates which determine anomalous transports[8][9]. An electron can move along the fluctuating field line freely, thus radial component of the velocity is $v_{th}B_r/B_T$, where v_{th}, B_r, and B_T are electron thermal velocity, radial component of the fluctuating field, and the toroidal magnetic field, respectively. A small magnetic fluctuation of $B_r/B_T = 10^{-4}$ can be a cause of anomalous electron transport[10][11]. In order to investigate the possibility that the magnetic fluctuations have dominant contribution to the anomalous thermal conductivity in the tokamak plasma, magneto-hydrodynamic (MHD) activities have been observed by external pick-up coils in the L-mode and the H-mode with three types of magnetic configurations (single null divertor, D-shaped limiter, and fully expanded limiter discharges) of the JFT-2M tokamak, and a clear correlation has been found between a H-transition and a reduction of magnetic fluctuations (both of a low frequency m=2 mode (f = 4 kHz) and high frequency fluctuations (f > 10 kHz)). Concerning about high frequency fluctuation, similar observation has been reported in the Doublet III[11], where the fluctuation is incoherent in both frequency spectrum and geometrical structure, and has high m poloidal mode number($m > 8$). In addition to divertor H-mode, the magnetic fluctuation of the H-mode-like limiter discharge is described also.

2. EXPERIMENTAL ARRANGEMENT

The JFT-2M tokamak has a D-shaped vacuum vessel ($R_V = 1.31$m, $a_V = 0.415$m, $b_V = 0.595$m) made of stainless steel of 25mm thickness[12]. The skin time of the vessel for the poloidal magnetic field is about 7msec. The minor radii of the full plasma are $a_p = 0.35$m and $b_p = 0.53$m. The maximum value of toroidal field and plasma current are 1.4T and 550kA, respectively. Divertor configurations (single null/double null) are also achieved. Graphite divertor plates are installed at the top and bottom of the vessel. There are also two sets of poloidal limiters made of graphite blocks.

The improved confinement can be obtained not only in divertor discharges (single null/double null) but also in limiter discharges in the JFT-2M with tangential H^0-NBI or ICRF heating[7]. Detailed investigation of the magnetic fluctuations with the co-injection of H^0 beam into deuterium plasmas are described in the present paper.

Magnetic fluctuations in the JFT-2M tokamak are detected by an poloidal array of 24 pick-up coils which is located just inside the vacuum vessel as shown in Fig.1. Sampling frequency is typically 100kHz. Since a maximum number of measured pick-up coils are restricted to 12 by CAMAC modules, it is difficult to determine high m poloidal mode structure ($m > 5$) by this measurement. Frequency characteristics of a pick-up coil for time derivative of the magnetic field (dB/dt) is shown in Fig. 2. An upper cut-off frequency of 30kHz is determined by shielding elements against ICRF noise. Measured signals ($\dot{\tilde{B}}$) are integrated to obtain magnetic fields after compensation of the above frequency characteristics. Low frequency configurations (single null divertor, D-shaped limiter, and fully expanded limiter discharges) of the JFT-2M tokamak, and a clear correlation has been found between a H-transition and a reduction of magnetic fluctuations (both of a low frequency m=2 mode (f = 4 kHz) and high frequency fluctuations (f > 10 kHz)). Concerning about high frequency fluctuation, similar observation has been reported in the Doublet III[11], where the fluctuation is incoherent in both frequency spectrum and geometrical structure, and has high m poloidal mode number($m > 8$). In addition to divertor H-mode, the magnetic fluctuation of the H-mode-like limiter discharge is described also.

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3. EXPERIMENTAL RESULTS

3.1 Single Null Divertor Configuration

H-mode can be obtained very easily in a single null divertor configuration in the JFT-2M tokamak. A plasma shape determined by magnetic field fitting calculation is shown in Fig.3, where dots represent the position of limiter surface. The plasma current is 255kA. The distance between the null point and the divertor plate is about 6cm. The toroidal magnetic field is 1.24T and a ∇B drift of ions is downward. Neutral beam of 400kW (32keV, H^0-beam) is injected from 700ms to 900ms to the deuterium plasma. Figure 4 shows a temporal evolution of the plasma parameters, where P_{NBI} is a net input power of the neutral beam injected into the vacuum vessel. A transition from L-mode to H-mode can be seen at 753ms. The emission level of Balmer α line of hydrogen and deuterium ($H\alpha/D\alpha$), which is measured along a horizontal cord on the midplane, goes down abruptly at this transition, and a line averaged electron density ($\bar{n}_e$) measured by a HCN laser interferometer along a vertical cord begins to increase. Therefore a particle confinement time is improved in the H-mode. A radiation loss power (P_R) from the main plasma begins to decrease at the transition, but begins to increase about 10ms after the transition. Improvement of gross energy confinement can be seen in increase of a stored energy (DIAMAG) measured by diamagnetic loops.

The signals detected by any pick-up coils have clear correlations to H-mode transition. Magnetic fluctuations detected by $\tilde{B}$-21 decrease abruptly at the transition as shown in Fig.4.(b). Observed fluctuations exist in both the ohmic heating and the L-mode phase, and their envelope in the H-mode is reduced by a factor of 5 to 10 of magnitude. Time expansion of the magnetic fluctuation at the transition is also shown in Fig.4(b). It has a low frequency component, which is dominant component and whose frequency is 4kHz, and higher frequency components. Reduction of the low frequency component without a frequency change at the transition indicates that an MHD activity is stabilized without the stop of the poloidal mode rotation.

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The poloidal structure of the low frequency fluctuation measured by 12 pick-up coils at t = 740ms are presented in Fig.5. Horizontal axis is time in ms and the vertical axis represents poloidal location (∿ poloidal angle). Positive equi-surfaces of fluctuating magnetic field are traced in this figure. The number of positive zones at a vertical cut in this figure indicates that the poloidal mode number is 2. Direction of wave propagation coincides with electron diamagnetic direction in this case. Amplitude is about 1.5Gauss at the position of the pick-up coil. This fluctuation may correspond to a tearing mode.

High frequency components (f > 10kHz) included in $\tilde{B}$-21 is shown in Fig.4(c). Their poloidal structure is not well understood. The high frequency components are also reduced in the H-mode. Amplitude of the high frequency fluctuation is about 0.4 Gauss at the position of the pick-up coil in both ohmic and L-mode phases. These values correspond to $B/B_T = 3 \times 10^{-5}$. The amplitude of the fluctuations are not changed by the NBI heating.

3.2 D-shaped limiter discharge

The reduction of the magnetic fluctuations can also be seen in a limiter H-mode-like transition. Plasma shape is shown in Fig.6. In this case, upper movable graphite limiter was inserted and determined the plasma surface. Plasma current is 285kA, and toroidal field is 1.24T. Co-injection of 1MW neutral beam is applied from 700ms to 900ms. Temporal evolution of plasma parameters is also shown in Fig.6. Since H-to-L and L-to-H transition are frequent and duration of H-mode is short, improvement of the stored energy in the limiter discharge is smaller than in the divertor configuration. The emission of Hα/Dα and other signals at the H-to-L transition are quite similar to the divertor case. A behavior of the radiation loss power is rather complicated because contributions from both tendencies to increase about 10ms after the transition and to decrease in the L-mode are included. The magnetic fluctuations decrease at the L-to-H transition, and grow rapidly at the H-to-L transition. The amplitude of the fluctuations grow gradually after the beam injection and during the L-mode. Therefore these fluctuation may have a relation with the confinement deterioration in the L-mode. The correlation between the fluctuations and the deterioration has been observed more clearly in a fully expanded limiter discharge.

3.3 Fully Expanded Limiter Discharge

There is a fully expanded limiter discharge configuration in which magnetic fluctuations detected by some pick-up coils seem to have good correlation to the confinement deterioration in L-mode plasma as shown in Fig.7. The top and bottom of the plasma surface touch the divertor plates. The plasma current and the toroidal field are 288kA and 1.23T, respectively. There is no H-transition during the 1.2MW NBI heating. High frequency fluctuations ($f > 10kHz$) of the pick-up coils located just behind the divertor plates, such as $\tilde{B}$-4, $\tilde{B}$-5, $\tilde{B}$-21 and $\tilde{B}$-22, increase just after a few msec of beam injection by a factor of 5. The other pick-up coils signals do not have such a time behavior. Furthermore, these coils do not detect the increase of fluctuation clearly by the beam injection in other configurations, such as the single null divertor or more circular limiter configuration as shown in Fig.3 and Fig.6. An explanation is possible if these fluctuations have high m mode structures. Since locations of B-21 and B-22 are sufficiently near the plasma surface in the configuration shown in Fig.7, a high m magnetic fluctuation, which give a magnetic field $\tilde{B} \sim (r_p/r_s)^{-m-1}$ in the region between the plasma the wall, can be detected. Here r_s is a distance between the plasma surface and the plasma center, and r_p is a distance between the pick-up coil and the plasma center. The value of (r_p/r_s) is ~ 1.1. The other pick-up-coils could not detect the fluctuation because their locations are more far from the plasma surface. $\tilde{B}$-21 could not detect these type of the fluctuations in the single null divertor configuration, where the value of (r_p/r_s) is ~ 1.7 and larger than in the configuration of Fig.7. The limiter discharge shown in Fig.6 is in a intermediate situation, where the value of (r_p/r_s) is ~ 1.3. From these results it is inferred that the poloidal mode number is high and $m > 5$.

4. SUMMARY AND DISCUSSIONS

Magnetic fluctuations are observed in the single null divertor configuration and the limiter discharges on the JFT-2M tokamak. It is observed that the wide band fluctuations (4kHz-50kHz) are well reduced in the H-mode. These fluctuation are already exist in the ohmically heated plasma. The poloidal mode number of the low frequency fluctuation ($f \sim 4kHz$) is 2 typically, and the direction of the mode propagation is electron diamagnetic

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The temporal behavior of the magnetic fluctuation is quite similar in the limiter H-mode-like discharge to that in the single null divertor configuration as other signals from the plasma are. It is suggested by the similarity that the physical mechanism of the H-transition is identical in the divertor configuration and the limiter discharge.

It seems that the fluctuations observed in the single null configuration do not induce the confinement deterioration in the L-mode, because their amplitudes do not change by the beam injection. On the other hand, there is still a possibility that these fluctuations are causes of the anomalous transport which exists in the ohmic heating phase. In fact the amplitude of the high frequency fluctuation ($\tilde{B}/B_T$) is 0.3×10^{-4} at the pick-up coil, and this order of magnitude is possible to explain the electron anomalous conductivity[10]. Furthermore, the above possibility is supported by the fact that the particle confinement time exceeds in the H-mode, where observed fluctuations are reduced, to that in the ohmic heating phase. The observed fluctuations are well suppressed during the H-mode even if the stored energy saturates or begins to decrease. Therefore the energy confinement time is not determined by these fluctuations. The radiation loss power from the main plasma, which increases rapidly and its profile tends to peak in the H-mode, may determine the confinement time in this phase. Other instabilities which is not detected here are also candidates.

Though the fluctuations observed in the divertor configuration may be some causes of the anomalous transport in the ohmically heated plasma, they are not dominant causes of the confinement deterioration in the L-mode as mentioned above. The high frequency (f > 10kHz) fluctuations which seem to have a good correlation to the confinement deterioration in the L-mode plasmas is observed in the expanded limiter discharge by some pick-up coils just behind the divertor plates. These fluctuations seems to have high m poloidal structures, and therefore they can not be observed in the configurations where the position of the pick-up coils are far from the plasma

surface. These fluctuations may be dominant causes of the confinement deterioration in the L-mode.

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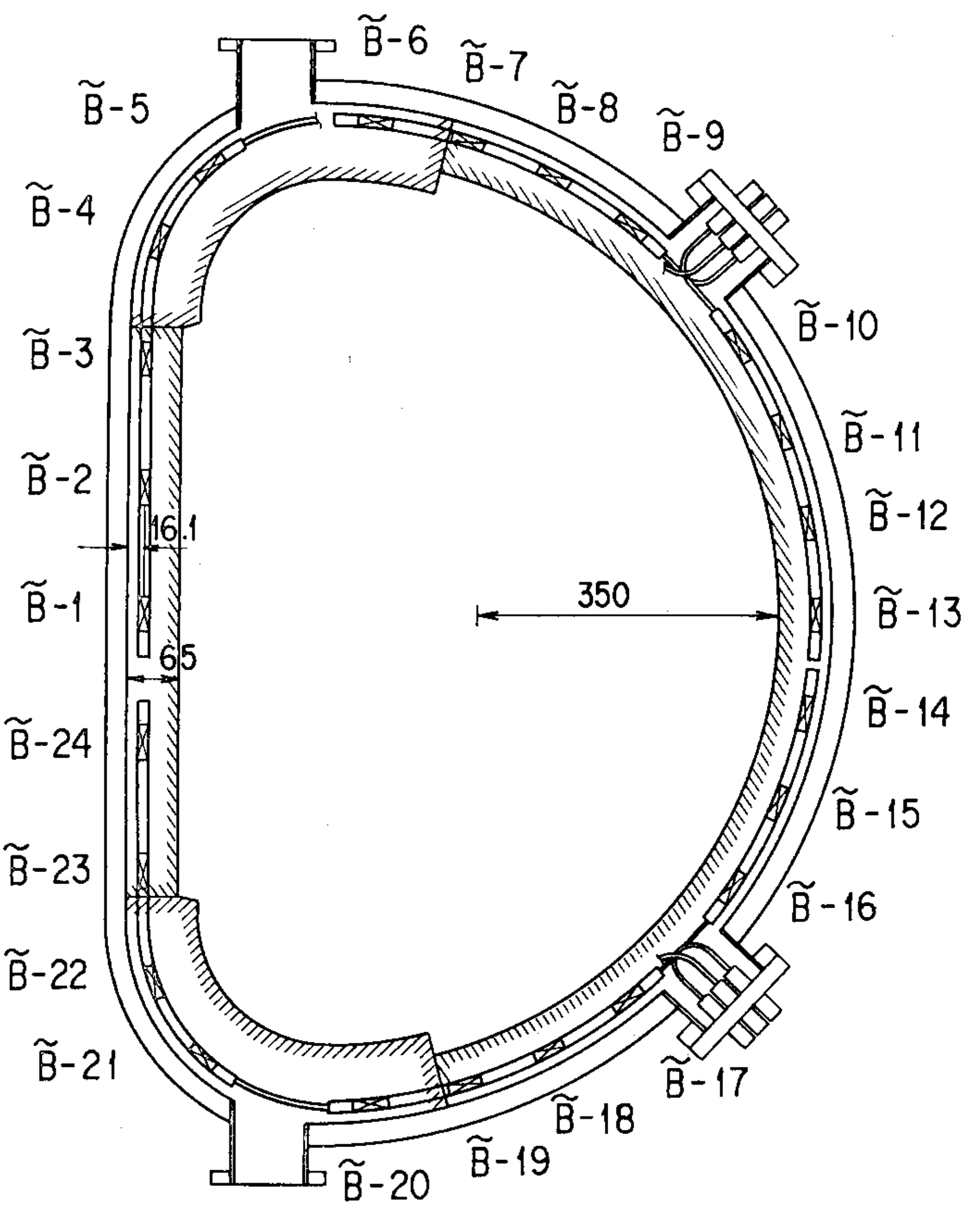

Fig.1 Location of pick-up coils for the measurement of the magnetic fluctuations. An array of 24 pick-up coils are located 16.1 mm inside from the vacuum vessel wall.

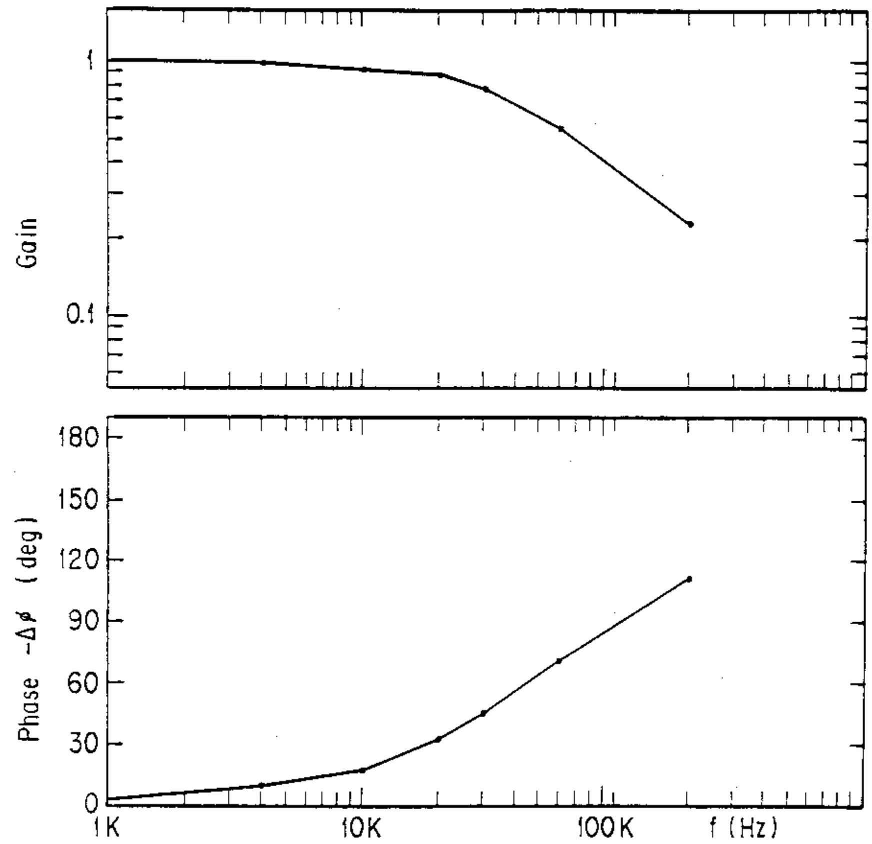

Fig.2 Frequency characteristics of a pick-up coil

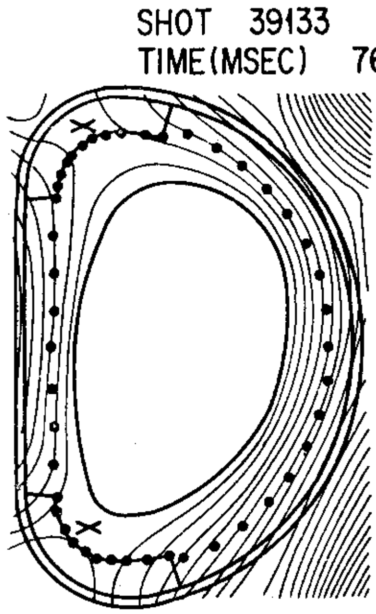

Fig.3 Plasma equilibrium in a single null divertor discharge.
Plasma cross section is determined from the magnetic field fitting calculation. Dots represent the positions of the limiter surface. Cross indicates a null point.

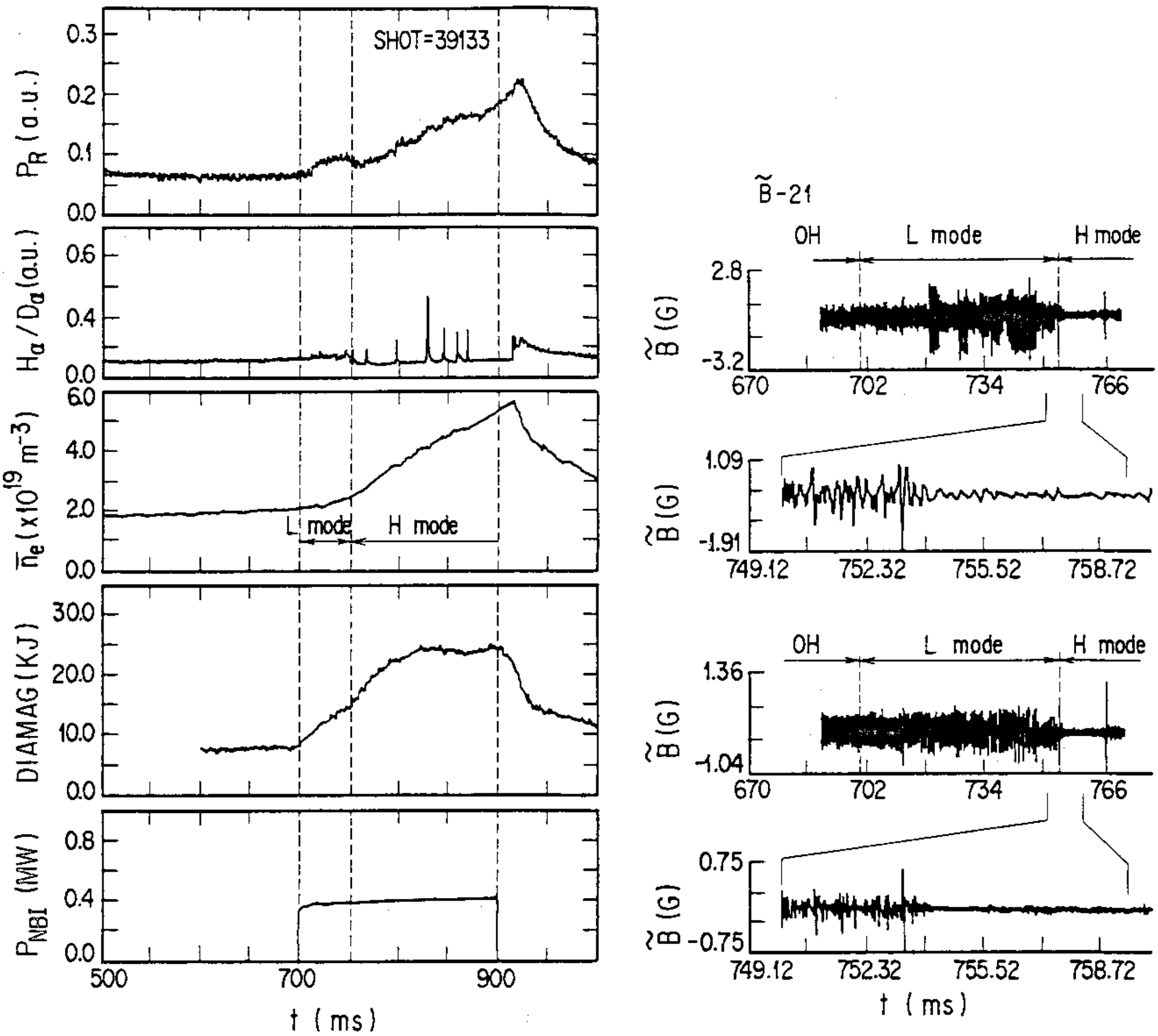

Fig.4 Temporal evolution of plasma parameters in the single null divertor discharge with NBI heating.
Neutral beam of 400kW (32keV H^0 beam) is injected in deuterium plasma from 700ms to 900ms tangentially.
L-to-H transition occurs at 753ms.
Correlation between H-transition and the magnetic fluctuations can be seen well.

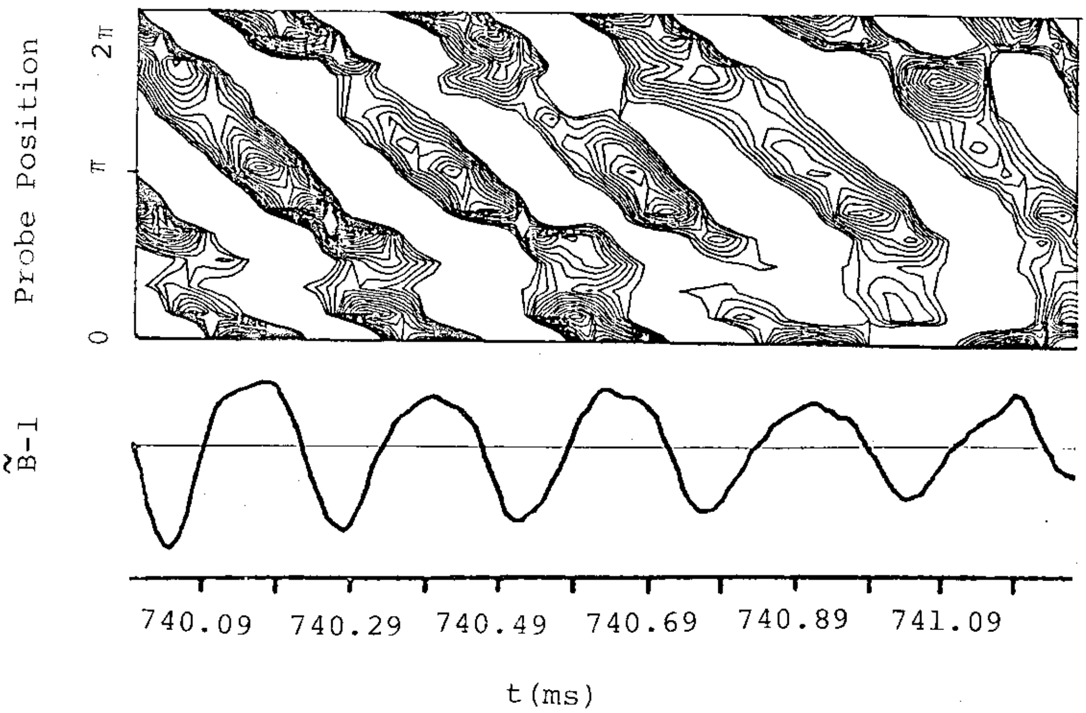

Fig.5 Poloidal mode structure measured by 12 pick-up coils. Equi-surfaces of fluctuating magnetic field are traced if it is positive. The number of the positive zones at the vertical cut indicates the poloidal mode number of dominant fluctuation, and it is 2 in this case.

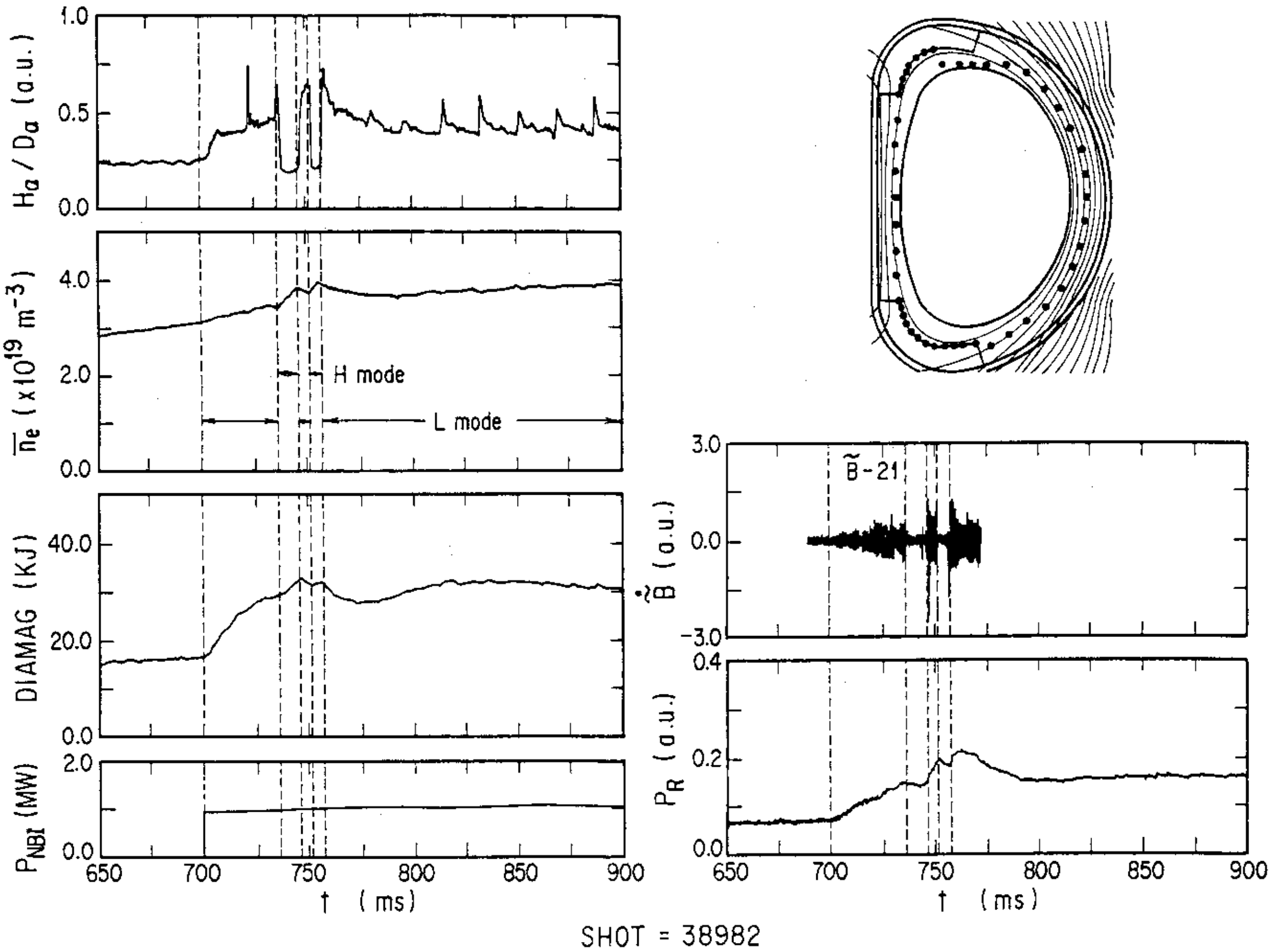

Fig.6 Temporal evolution of plasma parameters in a D-shaped limiter discharge with NBI heating. Neutral beam of 1MW is injected in deuterium plasma from 700ms to 900ms. In this discharge an upper movable limiter is inserted and determines the plasma boundary. Plasma equilibrium in the limiter discharge is also shown.

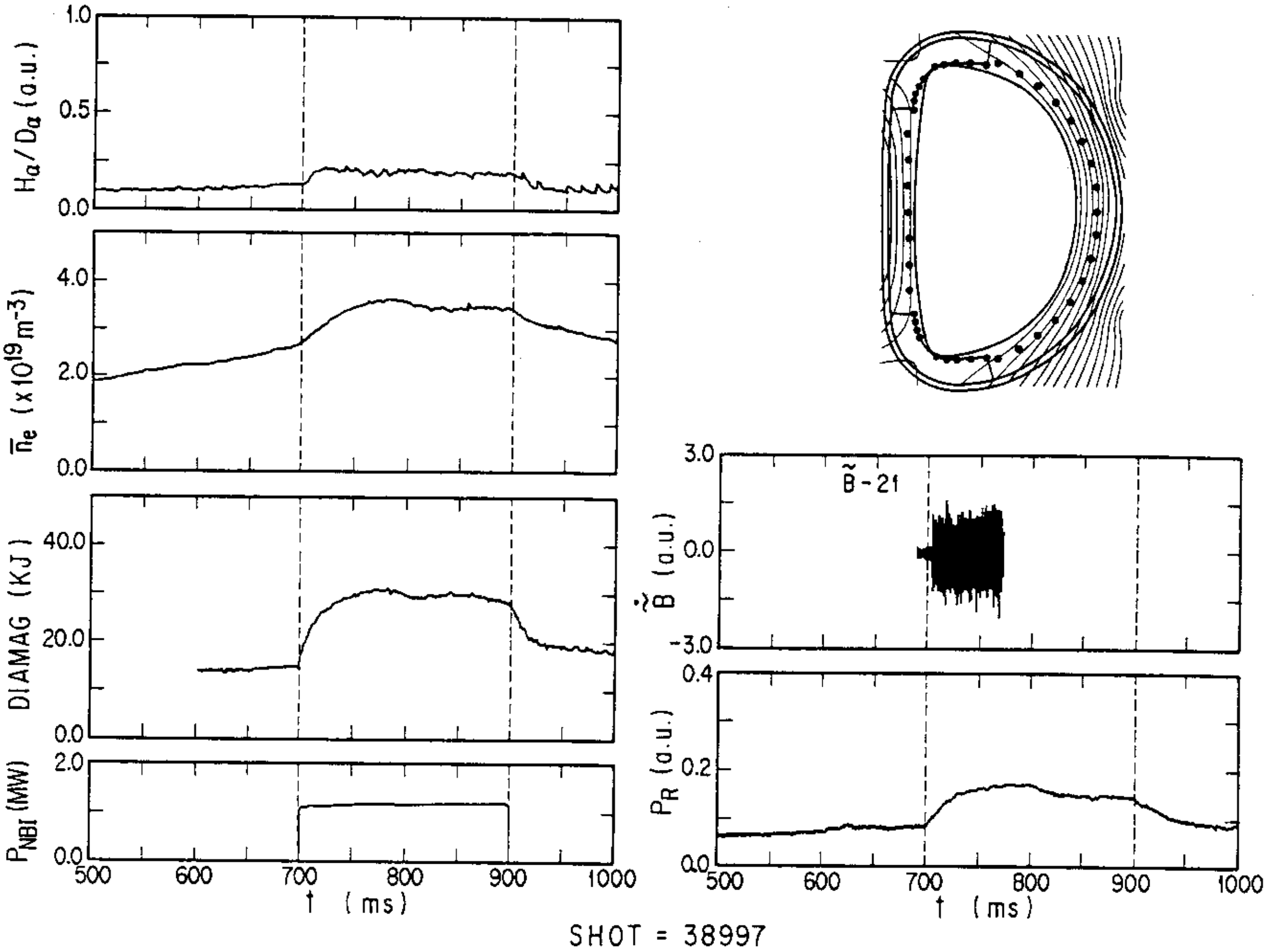

Fig.7 Tempral evolution of plasma parameters in a full expanded limiter discharge with NBI heating. Neutral beam of 1.2MW is injected in deuterium plasma. Plasma elongation is very large, and the top and bottom of plasma touch the graphite plates. There is no H-transition. The magnetic fluctuations detected by B-21 increase significantly by the beam injection.