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MAGNETIC FLUCTUATIONS DURING PLASMA CURRENT RISE OF DIVERTOR DISCHARGE IN JT-60

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Magnetic Fluctuations During Plasma Current Rise Of Divertor Discharge In JT-60

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During a current rise phase in the JT-60 divertor discharge, a series of magnetic fluctuations which do not rotate poloidally (phase-locking) is observed. They cause a cooling of plasma periphery and an enhancement of H_α emission in the divertor chamber. A significant increase in $\beta_p + l_i/2$ with minor disruptions during the phase-locked magnetic fluctuation suggests a relaxation of the current profile in the current rise phase of the divertor discharge.

Keywords: Magnetic Fluctuation, Phase-locking, Current Penetration
Current Rise Phase, Divertor

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JT－60ダイバータ配位におけるプラズマ電流立上げ時の磁場揺動

日本原子力研究所那珂研究所臨界プラズマ研究部
牛草 健吉・菊池 満・細金 延幸
林 和夫*・辻 俊二

（1986年2月21日受理）

JT－60のダイバータ配位におけるプラズマ電流立上げ時に，ポロイダル方向に回転しない一連の磁場揺動を観測した。この揺動は，主プラズマ周辺を冷却化しダイバータ室からのH_α線放射強度の増大をもたらす。この揺動の間，マイナーディスラプションを伴って$\beta_p + l_i / 2$が著しく増大し，この期間で電流分布の緩和過程が存在することを示唆している。

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I. INTRODUCTION

Magnetic fluctuations during the current rise of tokamak discharge have been studied in many tokamaks$^{(1-6)}$. It is thought to be important from the point of view of a non-classical current diffusion process. A series of magnetic fluctuations with decreasing poloidal mode number was observed in T-3$^{(2)}$ and T-4$^{(3)}$. These modes have caused an positive spike in the loop voltage and an increase in the plasma internal inductance. In ALCATOR-A a series of disruption related to the magnetic fluctuations with poloidal mode number m was observed when limiter q-value is nearly equal to 1.6 m$^{(4)}$. It was suggested by a numerical analysis of the current diffusion that disruptions appear when the local minimum q-value inside the plasma is nearly equal to an integral value. Two distinct types of MHD activity were observed in PDX$^{(6)}$. When the plasma current rises rapidly, magnetic fluctuations caused rapid increases in $\beta_p + l_i/2$ and in the loop voltage, while decreases in $\beta_p + l_i/2$ and in the loop voltage during the slow current rise.

In the divertor discharge a less interaction of the wall and the plasma may tend to form a steep current profile at the plasma edge. From the point of view of the current penetration in the divertor discharge, it is important to study MHD instabilities excited by a steep current profile at the plasma edge. Present paper shows observations of the magnetic fluctuations during the current rise of the divertor discharge in JT-60. Magnetic fluctuations with a poloidal mode number m are observed when an effective q-value near the plasma surface is about an integral value m. These fluctuations do not rotate poloidally and cause an enhancement of the edge transport. A cooling of the plasma periphery and an enhancement in the H_α in the divertor chamber are observed simultaneously with the phase-locked fluctuation. With minor disruptions during these fluctuations a significant increase in $\beta_p + l_i/2$ is observed.

The initial Ohmic heating experiment of JT-60 were carried out from April to June in 1985$^{(7)}$ with parameter ranges of $I_p = 0.5 - 1.6$ MA, $B_T = 2.5 - 4.4$ T, and $\bar{n}_e = 0.5 - 4.8 \times 10^{13}$ m^{-3}. The plasma current is built up to 0.7 MA typically during about the first 0.1 sec and then is increased with the current rise rate of typically 0.5 MA/sec. Stable discharges with a single null divertor located in the midplane radially outside the torus have shown favorable divertor effects. The plasma current up to 1.6 MA and the low-q discharge ($q(a) = 2.5$) have been demonstrated.

To measure magnetic fluctuations outside the plasma two sets of magnetic pick-up coils were used as shown in Fig. 1. The first set has 11 coils with spacing 30° in the poloidal direction at the single toroidal location (at #6 sector in Fig. 1). Signal of this set was converted to the frequency and then integrated by an up-down counter. These integrated signals are memorized with a sampling time of 1msec or 2msec. So that only low frequency magnetic fluctuations which have a frequency typically $f \leqq 100 - 200$ Hz is detectable by this set. The second set displaced 100° toroidally from the first (at #4 sector in Fig. 1) consists of 2 coils which are located at ±30° poloidally with respect to the midplane of outside torus. These signals were directly memorized with a sampling time of 50 μsec for a time interval 0.8 sec. Although relatively high frequency fluctuations ($10 \text{ Hz} \leqq f \leqq 3 \text{ kHz}$) are observable by this set, the poloidal mode structure cannot be identified completely. All coils are located at a minor radius of about 1 m and detect azimuthal field.

2. EXPERIMENTAL OBSERVATIONS

When the effective q-value near the plasma surface is about an integral value, the magnetic fluctuation appears in the magnetic pick-up coil. An abrupt increase in the loop voltage is observed simultaneously with the magnetic fluctuation. Figure 2 shows the plasma current I_p at the onset of the increase in the loop voltage for given B_T. To avoid a singularity in the usual definition of surface q-value at the plasma surface of the divertor configuration, we employed an effective q-value near the plasma surface as follows;

$$q_{eff} = \frac{2\pi a^2 B_T}{\mu_0 R_o I_p} \left[1 + \left(\frac{a}{R_o}\right)^2 \left\{ 1 + \frac{(\beta_p + l_i/2)^2}{2} \right\} \right] \qquad (1)$$

where a, R_o, I_p, B_T, β_p and l_i are the minor radius, the major radius, the plasma current, the toroidal magnetic field, the poloidal beta and the plasma internal inductance, respectively. Solid lines in Fig. 2 are calculated from Eq. (1) by using typical parameters in the divertor midplane radially outside the torus have shown favorable divertor effects. The plasma current up to 1.6 MA and the low-q discharge (q(a) = 2.5) have been demonstrated.

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Typical magnetic fluctuations of $q_{eff} \sim 4$ under almost the same conditions in the limiter and divertor discharges are shown in Fig. 3. Maximum fluctuation level $\tilde{B}/B_p$ (where $B_p = \mu_0 I_p/2\pi a$ is the static poloidal field) in the limiter case is about 0.13% with a frequency $f \sim 550$ Hz at $t \sim 2.08$ sec. In the divertor case the loop voltage increases at $q_{eff} \sim 4$ and then minor disruption occurs. Relatively low frequency magnetic fluctuation which oscillates only a half or one period at a frequency $f \sim 150$ Hz with $\tilde{B}/B_p \sim 0.7\%$ is observed at the time just before $q_{eff} = 4$ (at $t \sim 1.52$ sec). After this change bursts in the magnetic fluctuation is shown at the same time with the loop voltage disturbance. The minor disruption at $t \sim 1.56$ sec causes strong bursts in the magnetic fluctuation. We can say that higher MHD activity is observed during the current rise in the divertor discharge than in the limiter and the magnetic fluctuation in the divertor discharge does not show usual sinusoidal oscillations.

MHD activities at $q_{eff} \sim 3$ are shown in Fig. 4. The time evolutions of the plasma current I_p and the effective q-value q_{eff}^{MF} are shown in Fig. 4(a) and the loop voltage V_l and the $\beta_p + l_i/2$ are shown in Fig. 4(b). The $\beta_p + l_i/2$ and the effective minor radius are calculated by the first boundary identification code using 12 magnetic pick-up coil signals, poloidal coil currents and the plasma current. Using these values, Eq. (1) gives the effective q-value q_{eff}. Fig. 4(c) shows the relative change of the fluctuation level from the time t_0 just before the fluctuation; $\Delta b_\theta \equiv (\tilde{B}(t)/B_p(t)-\tilde{B}(t_0)/B_p(t_0))$, where coil signal at the poloidal angle $\theta = 30°$ is used. The H_α emission in the divertor chamber is shown in Fig. 4(d). After q_{eff}^{MF} becomes less than 3, the loop voltage increse abruptly and the discontinuity in the plasma current is observed. Simultaneously the magnetic fluctuation Δb_θ appears and a significant enhancement of the H_α emission (and also of the bolometer signal) in the divertor chamber is detected. It is noted that Δb_θ trace shows only about a quarter period of sinusoidal oscillation during a time interval of about 6msec. Almost the same behaviors are observed also in the time derivative signal of the magnetic fluctuation measured by coils in the #4 sector.

Figure 4(e) shows the poloidal patterns of Δb_θ measured by all coils in the #6 sector. The radius of the circle in Fig. 4(e) corresponds to the fluctuation level of 1.2%. The perturbation which has a poloidal mode number m = 3 is formed at the time t_1 and is kept at least until t_2 without the poloidal rotation. Strong perturbations in the magnetic field due to the inward shift of the plasma column are observed during the minor disruption at t ~ 1.83 sec. After the disruption the m = 3 structure is still kept without rotation but the change in the poloidal magnetic field by the outward shift of the magnetic axis due to the increase in $\beta_p + l_i/2$ are superimposed as shown in Fig. 4(e) (at t = 1.85 sec). The m = 3 fluctuation disappears at t ~ 2.07 sec simultaneously with the disappearance of the H_α emission in the divertor chamber. Before and after these activities $\beta_p + l_i/2$ increases to 0.6 from 0.48.

These phenomena such as the increase in the loop voltage, the H_α enhancement, phase-locked fluctuation and so on, are always observed in the divertor discharge when the effective q-value is nearly equal to an integer. An similar example of the case in which $q_{eff} \sim 5$ occurs just before the current flat top at t ~ 0.9 sec is shown in Fig. 5. Figure 5(a), (b) and (c) show the relative magnetic fluctuation level measured at the poloidal angle of 30°, 60° and 300°, respectively. In order to show only fluctuation signals, the change of the poloidal field due to the increase of $\beta_p + l_i/2$ is cancelled out by using $\beta_p + l_i/2$ calculated from the magnetics. The H_α emission in the divertor is shown in Fig. 5(d) and profiles of the fluctuation at the typical time are shown in Fig. 5(e). Large spike in the fluctuations and in the H_α emission at t ~ 1.05 sec is due to the poloidal power supply(8). Apparently we can see from the time evolutions of the fluctuation and their profile in the poloidal plane that the fluctuation of m = 5 does not rotate poloidally. At the time t_4, both the enhancement of H_α emission and the phase-locked fluctuation disappear. Clear correlation between the phase-locked fluctuation and the H_α in divertor chamber are observed.

Although two sets of pick-up coils separated by 100° toroidally each other were employed in this experiment, a lack of the number of coil in the #4 sector in addition to the less oscillation of phase-locked fluctuation make it impossible to identify the toroidal mode number n. These fluctuations are always locked poloidally in the same phase for the same q_{eff}.

Figure 6 shows the profiles of the line-integrated soft x-ray signal measured by 5ch pin diode array before and during the H_α enhancement. The signal from the outermost chord (d/a ~ 0.78) decreases to about 60% of the initial value at about 50msec after the onset of H_α enhancement and keep its value during the phase-locked fluctuation. After the fluctuation the signal recovers to almost the initial value. Change of signal from other chords is modest compared with that from the outermost. It may be considered that the cooling of the plasma periphery is caused by the enhancement of the edge transport associated with the phase-locked fluctuation as observed in the H_α enhancement (and also in the radiation loss from the divertor plasma).

A high rate of the plasma current rise has led to a large increase in the loop voltage, strong minor disruptions, high activities in the magnetic fluctuations and consequently a large increase in $\beta_p + l_i/2$. Figure 7(a) and (b) show the time evolution of $\beta_p + l_i/2$ calculated by the magnetic fitting code for the rate of current rise $\dot{I}_p$ = 0.72 MA/sec and for 0.5 MA/sec, respectively. Other parameters except the plasma current in flat top are almost the same. Increase in $\beta_p + l_i/2$ for $\dot{I}_p$ = 0.72 MA/sec are larger than that for 0.5 MA/sec by factor 2, for example, at $q_{eff} \sim 4$ $\Delta(\beta_p + l_i/2) \sim 0.133$ and 0.075 for $\dot{I}_p$ = 0.72 MA/sec and for 0.5 MA/sec, respectively. The electron temperature measured by the soft x-ray pulse height analyzer and the line-integrated electron density near the plasma center show no significant change during these phase-locked fluctuation. Soft x-ray signals measured by the pin diode array show no significant change in the temperature profile except for the edge region. Then we can say that the increase in $\beta_p + l_i/2$ is due to mainly the increase in the plasma internal inductance l_i.

The reason why magnetic flucutations do not rotate poloidally in the JT-60 divetor discharge is still an open question. It should be noted that experimental observations show the clear correlation between the phase-locked fluctuation and the edge transport. MHD fluctuation near the plasma surface leads to a deterioration of the edge confinement. However no unfavorable effects in the plasma at current flat top are observed except for the case with strong minor disruptions when the plasma current is rising rapidly. When a more rapid current rise is required, a current profile control during the current rise phase such as a ramp up with the constant q_a should be employed in order to avoid such strong minor disruptions.

3. SUMMARY

During the current rise of the divertor discharge in JT-60, the current penetration process are observed with following phenomena:

(1) The magnetic fluctuation of $\tilde{B}/B_p \leqq 1.5\%$ which has a poloidal mode number m and does not rotate poloidally is observed when the effective q-value near the plasma surface is nearly an integral value. Simultaneously with phase-locked fluctuation the loop voltage increases ($\Delta V_1 \leqq 5V$) and the discontinuity in the plasma current is observed and then minor disruptions occur under certain conditions.

(2) The soft x-ray signal from outer plasma decreases and the H_α emission in the divertor chamber increases during the phase-locked fluctuation, while signals from the central region of the plasma are not affected by the fluctuation.

(3) Significant increase in $\beta_p + l_i/2$ is observed after the fluctuation ($\Delta(\beta_p + l_i/2) \leqq 0.15$). This increase is supposed to be mainly due to the increase in l_i.

A high rate of the current rise and a low q_{eff} tend to cause a high current penetration during the phase-locked fluctuaton.

ACKNOWLEDGEMENTS

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7. YOSHIKAWA, M., and JT-60 Team, in Controlled Fusion and Plasma Physics (12th Europ. Conf., Budapest, 1985)
8. SHIMADA, R., private comminucation; When some thyristor convertors on the poloidal power supplies are bypassed to avoid a current concentration, a voltage spike on the poloidal coils appears. Large spikes in Fig. 5 are due to a disturbance in the poloidal magnetic field caused by this voltage spike.

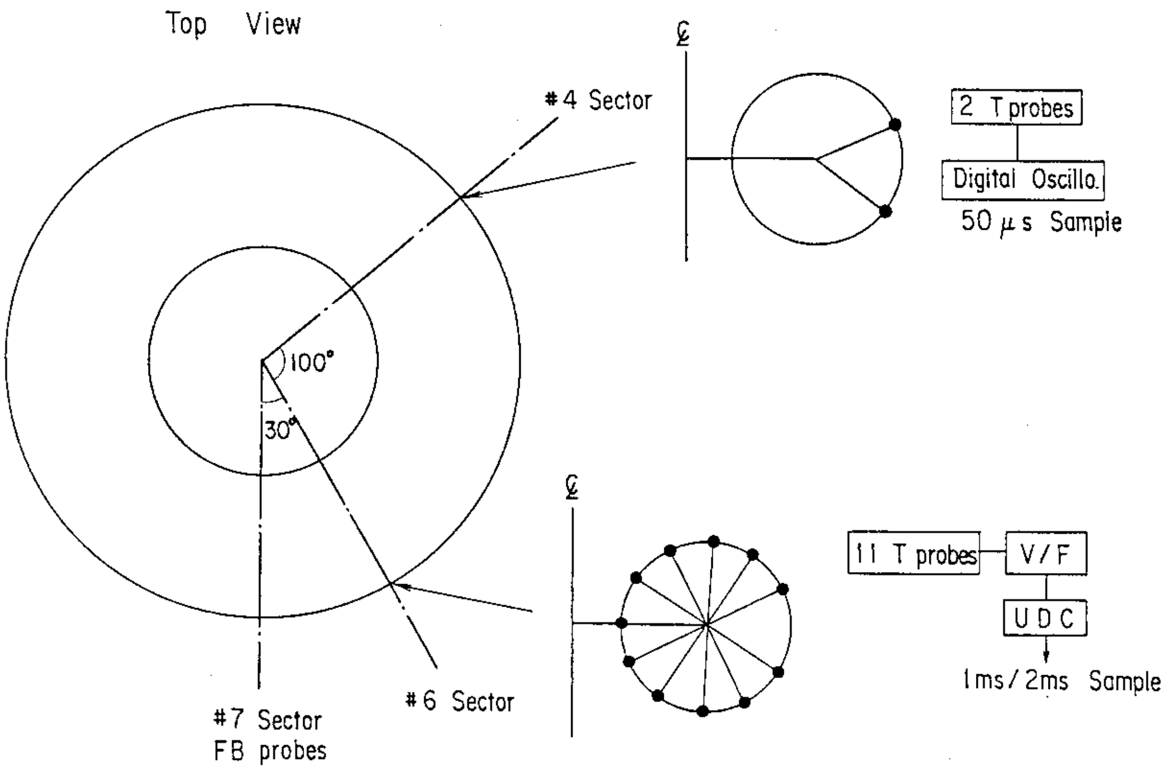

Fig. 1 Arrangement of employed magnetic coils. Coil signals in the #6 sector are integrated by up-down counter (UDC) after they are converted to the frequency by V/F converter, and memorized with a sampling pitch of 1msec or 2msec. Signals from the #4 sector coil are directly memorized with a sampling pitch of 50 μsec. T probe means the magnetic coil which detects azimuthal field.

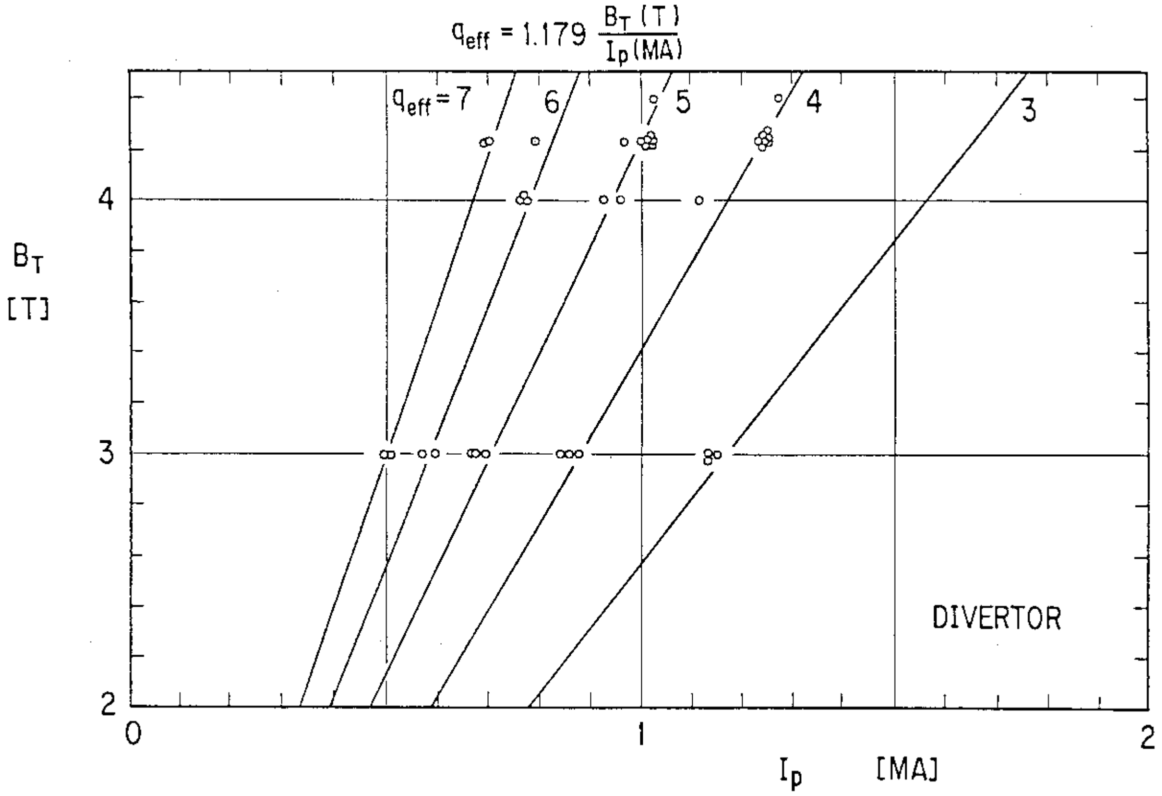

Fig. 2 Relation between the effective q-value and the plasma current at the onset of the increase in the loop voltage in the divertor discharge. Open circles show the experimental data and solid lines show the effective q-value calculated from Eq. (1) for $a = 0.83$ m, $R_o = 3.15$ m and $\beta_p + l_i/2 = 0.5$.

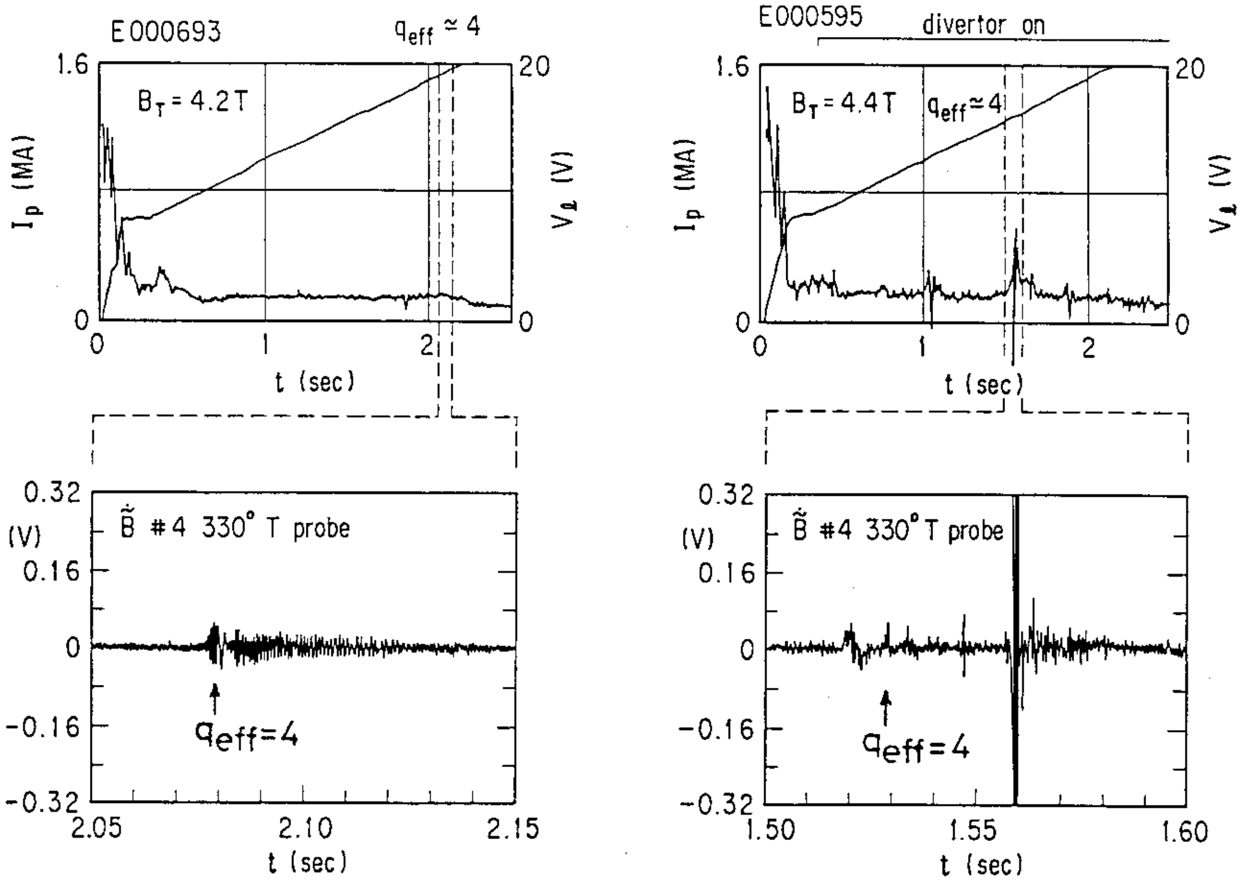

Fig. 3 Comparision of the magnetic fluctuation of $q_{eff} \sim 4$ in the divertor discharge (the right hand side) with that in the limiter (the left hand side). Upper traces show the plasma current I_p and the loop voltage V_l, while lower traces show the magnetic fluctuation $\dot{\tilde{B}}$ measured by the #4 sector coil.

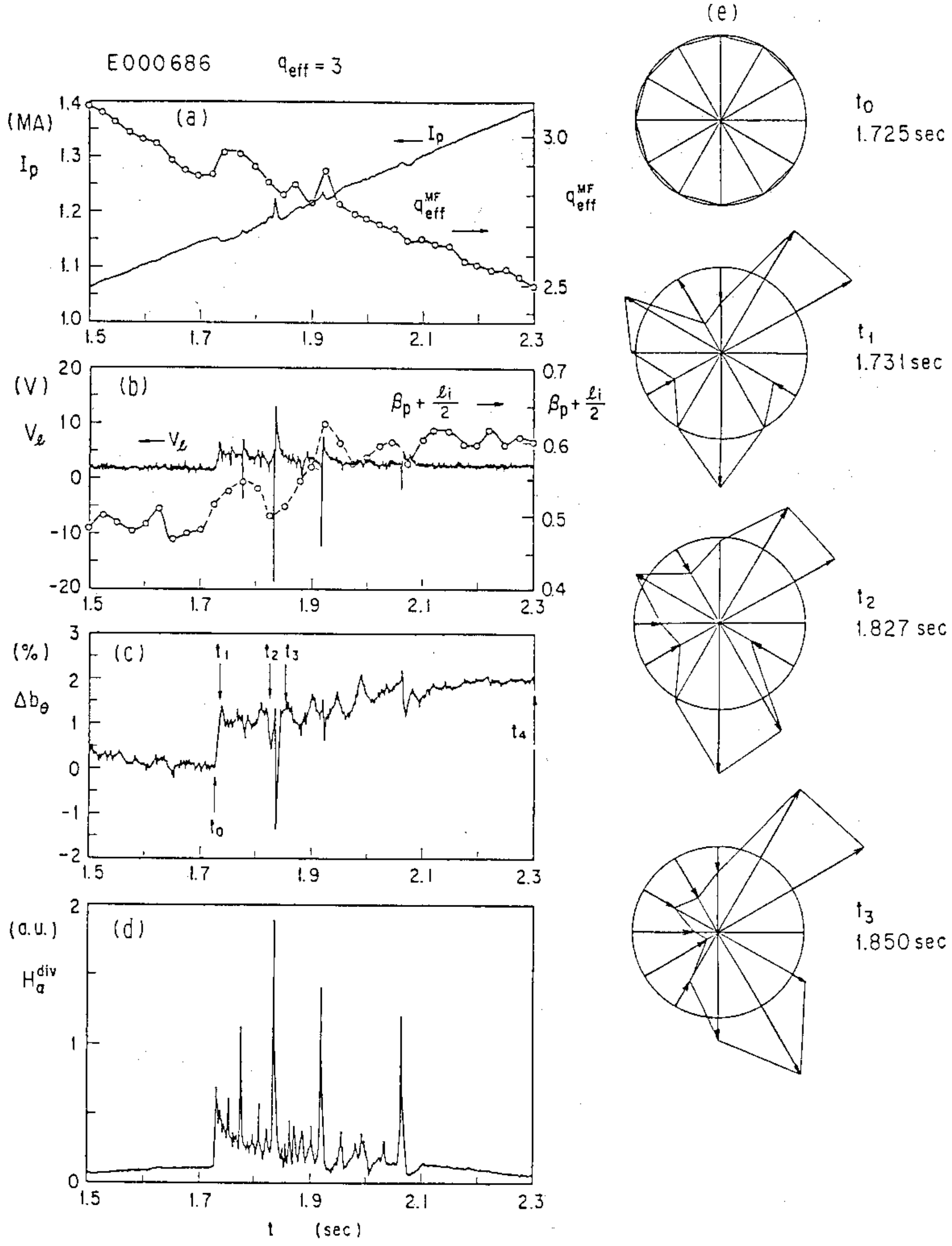

Fig. 4 MHD activities at q_{eff} ~ 3 (B_T = 3T). (a); the plasma current I_p and the effective q-value calculated by the magnetic fitting code q_{eff}^{MF}. (b); the loop voltage V_l and $\beta_p + l_i/2$ by the fitting code. (c); the relative change in the magnetic fluctuation level Δb_θ measured at the poloidal angle of 30°. (d); the H_α emission in the divertor chamber. (e); Profiles of the Δb_θ in the poloidal plane at t_1 ~ t_3 as shown in (e). Radius of the circle corresponds to the fluctuation level of 1.2%.

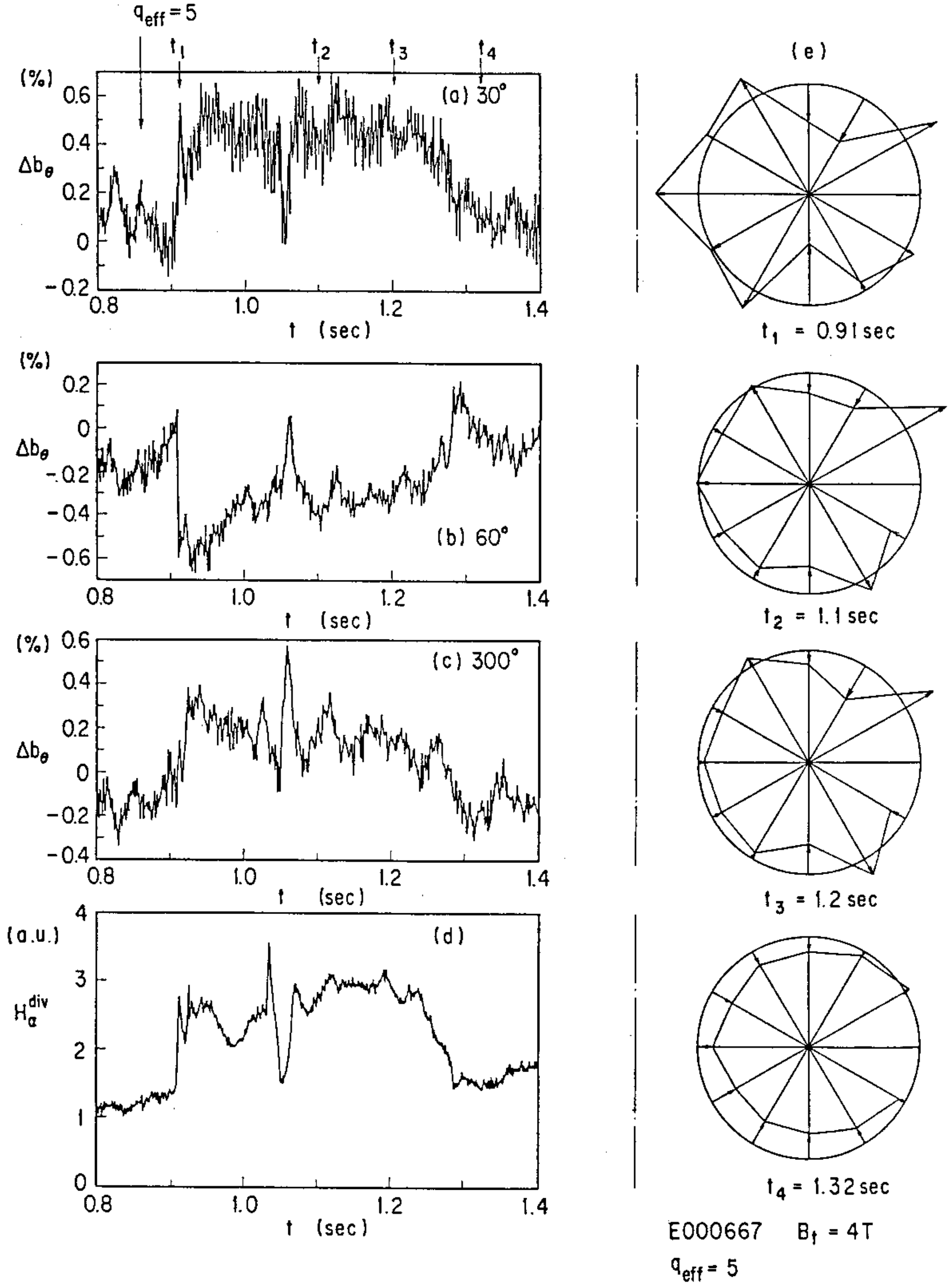

Fig. 5 MHD fluctuation at $q_{eff} \sim 5$ (B_T = 4T). (a),(b) and (c); the relative fluctuation level at the poloidal angle of 30°, 60° and 300°, respectively, where the change in the poloidal field due to the increase in $\beta_p + l_i/2$ is cancelled out. (d); the H_α emission in the divertor. (e); profiles of Δb_θ at t = 0.91 sec, 1.1 sec, 1.2 sec and 1.32 sec.

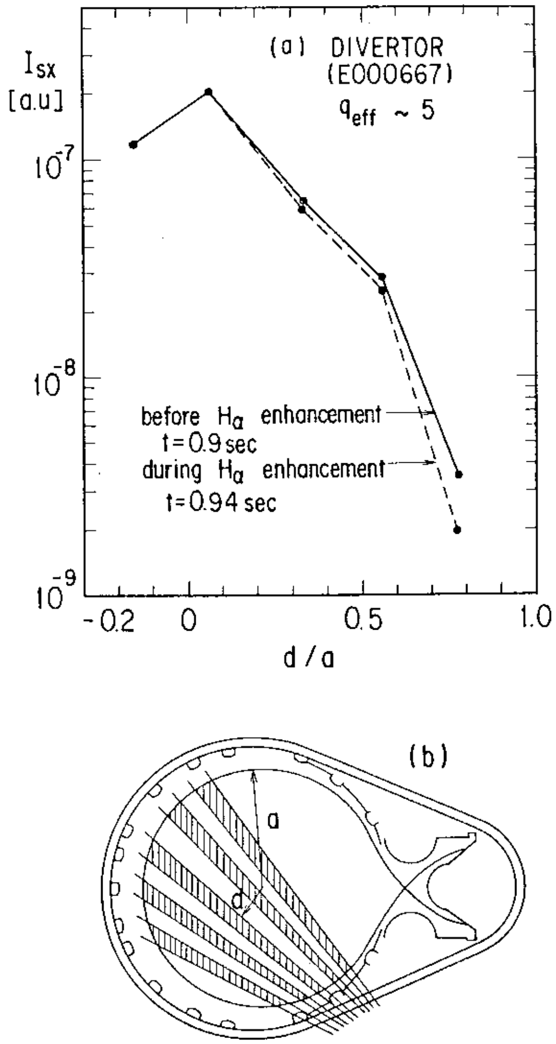

Fig. 6 Profiles of the line-integrated soft x-ray signal measured 5ch pin diode array before and during the H_α enhancement (a), and their chords in the poloidal plane (b).

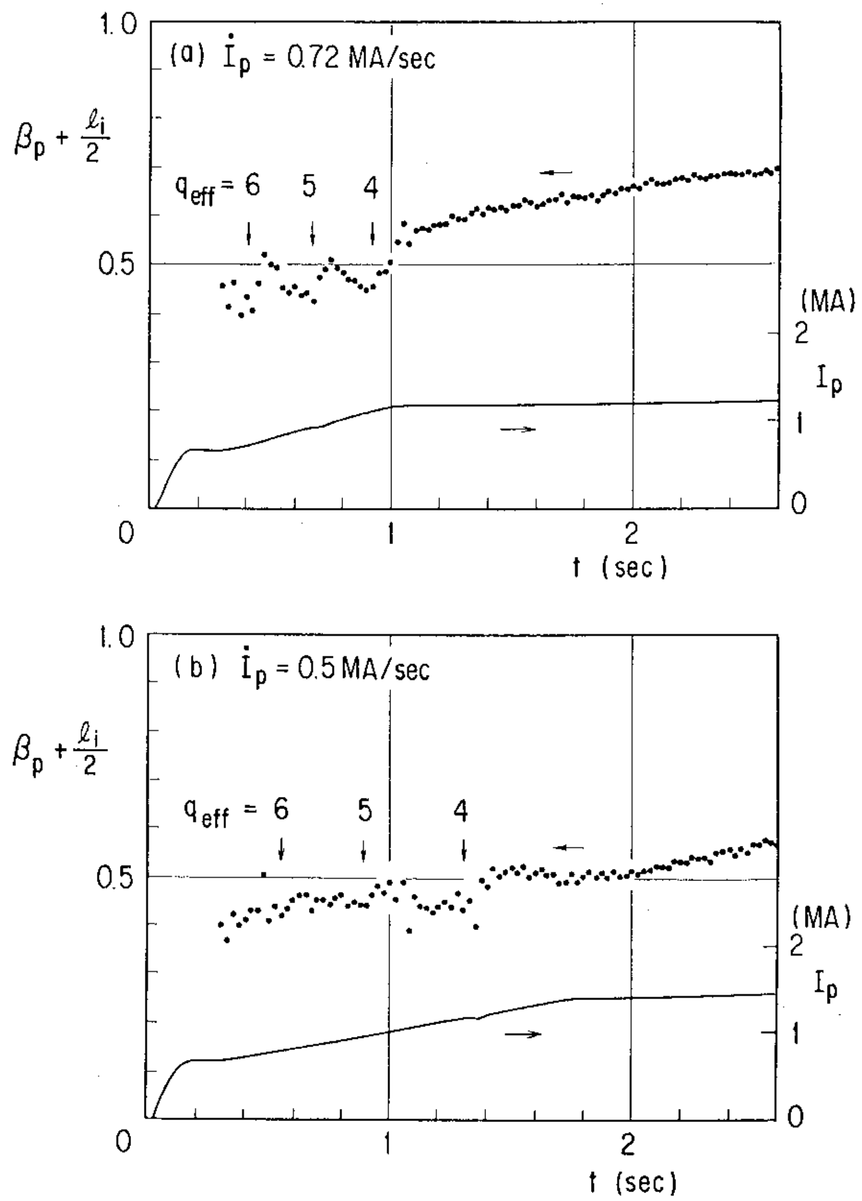

Fig. 7 Time evolutions of $\beta_p + l_i/2$ by the fitting code and the plasma current I_p for $\dot{I}_p$ = 0.72 MA/sec (a) and for 0.5 MA/sec (b). B_T = 4T.