

Mode Locking in Iran-Tokamak1 (IR-T1)

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An $(m = 2)/(n = 1)$ locked mode has been observed in Iran-Tokamak1 (IR-T1) at safety factor $q = 2.5$ during the plasma current flattop phase, and in this paper its main characteristics have been studied. It has also been shown that investigating the precursor phase of disruption may lead to predication of the disruption.

INTRODUCTION

In the ideal magnetohydrodynamic (MHD) model, considering the Ohm law $\vec{E} + \vec{V} \times \vec{B} = 0$, it is required that the plasma moves with the magnetic field; thus, it has been generally believed that ideal MHD instabilities cannot change the topology of the flux surfaces. However in real plasmas, such as those contained in tokamaks, finite plasma resistivity and other irreversible kinetic effects admit collective magnetic perturbations that can 'break' or reconnect magnetic field lines and thereby allow a resistive tearing mode to form. The magnetic flux surfaces produced by the toroidal and poloidal magnetic fields is defined by $B_\theta = \sum A_{mn} \exp[i(\omega_{mn}t - m\theta - n\phi)]$ [1] where θ and ϕ are the poloidal and toroidal angles, m and n are poloidal and toroidal mode numbers, respectively, and ω is the angular frequency of the (m, n) mode in the laboratory frame. When low m/n tearing modes are unstable, some magnetic islands are formed in the plasma. If the instability continues, the plasma current in the island region increases the strength of the local helical field, and thus the island size, until a critical island width is reached [2,3]. Beyond this region, the plasma is unstable and the tearing modes grow dynamically, until an additional non-linear effect, such as current profile flattening, stabilizes the mode at an enhanced level. If

the island grows too large before the stabilization takes place, adjacent modes can overlap and the disruption occurs [4]. For some types of disruption, because of the penetration of the magnetic field into the torus wall and production of eddy currents, the wall applies a force to the plasma, which stops rotating and finally results in mode locking [5]. Locked modes significantly limit the operating parameters of the tokamaks by causing confinement degradation [6]. The lock mode that has been observed in every tokamak (e.g., JET [7], JT-60U [8], DIII-D [6], COMPASS-C [9] and TEXTOR [10]), has also appeared in IR-T1 at the plasma current flattop phase.

Considering this point of view, the study of precursor phase of disruption is very important, because the disruption can be predicted and avoided using suitable control systems. For example, magnetic feedback control has been used in the Divertor Injection Tokamak Experiment (DITE) to reduce saturated $(m = 2)/(n = 1)$ instabilities [11,12].

In this paper, characteristics of a lock mode, obtained from the presented experimental results, are presented and the precursor phase of the disruption has been investigated.

EXPERIMENTAL ARRANGEMENT

The IR-T1 is a conventional tokamak with major and minor radii of 45 cm and 12.5 cm, respectively, with a circular cross-section using a material limiter of minor radius of 11.5 cm. Maximum plasma current used is 48 kA with a toroidal magnetic field of 0.7 T and mean electron density of $1.2 \times 10^{13} \text{ cm}^{-3}$. The safety factor generally defined as $q(a) = (a/R).(B\phi/Bp)$ obtained, is about 2.5. The magnetic fluctuations are detected

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with Mirnov coils located outside the vacuum vessel at a radius of about 18 cm. Operational regions of the IR-T1 tokamak has already been presented in [13-15].

EXPERIMENT AND RESULTS

Figure 1 shows the typical time evolution of a) Plasma current, b) Mirnov coil signal, c) OII impurity signal at the edge of the plasma and d) Electron Cyclotron Emission (ECE) signal. As shown in Figure 1a, the plasma current is divided into three phases. In the first phase (current ramp-up), an $(m = 3)/(n = 1)$ mode grows up at $t = 2.5$ ms, however, as the plasma current continues to increase, the MHD activity decreases, and thus this mode tends to be stabilized. In the second phase (current flattop), an $(m = 2)/(n = 1)$ mode grows up at $t = 15$ ms which is unstable as shown in Figure 1b. In the last phase (current quench) a small positive vertex is shown close to $t = 19.7$ ms. Figure 1b shows the oscillation of the $(m = 3)/(n = 1)$ mode at the current ramp up phase and the $(m = 2)/(n = 1)$

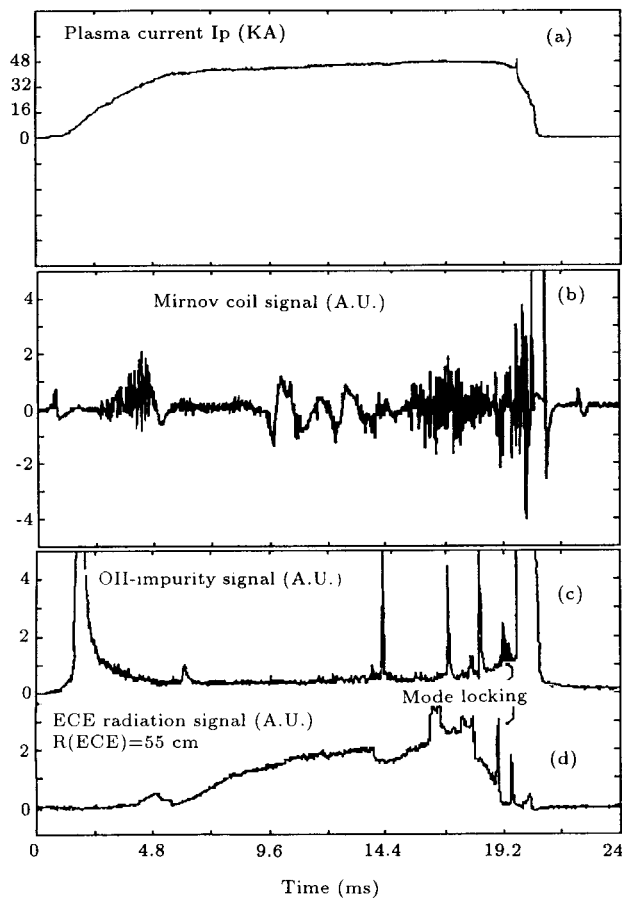


Figure 1. Time traces for a disrupting mode locking discharge; (a) Plasma current, (b) Mirnov coil signals, (c) OII-impurity signals at the edge of the plasma, (d) ECE radiation signals obtained at a location 10 cm apart from the center of the plasma.

mode in the flattop phase of the current. As shown in this figure the latter mode rapidly grows up and locks at $t = 19.1$ ms. Figures 1c and 1d show the OII impurity and ECE signals. These figures show large increases in the OII impurity radiation and also in the ECE signals at the current quench phase. As shown, the plasma magnetic activity observed in the Mirnov coils signal (Figure 1b), bursts just after the mode locking takes place, which is also observed by a large and distinct spike in the ECE signal.

The interval time between 18 to 22 ms in Figures 1b, 1c and 1d is expanded and shown in Figure 2. In this figure, energy quench and current quench times are about 0.8 ms and 0.4 ms, respectively. At phase energy and also current quenches, a strong radiative power loss from the OII impurity signal is observed. It has also been shown that in 19.1 ms the ECE spike and the OII impurity spike (Figures 2b and 2c) are both accompanied with the mode lock process in the precursor phase of disruption (Figure 2a).

Characteristics of discharges with locked modes are usually: Cessation of soft x-ray sawtooth, reduction of energy confinement, cessation of the plasma mode rotation at safety factor $q = 2$ and excessive radiative cooling at the plasma edge which is caused by the current channel shrink [16]. In another typical shot (Figure 3) the variation in loop voltage and Mirnov signal at time 10-16 ms is observed. Figure 3 shows the events immediately before and during the negative

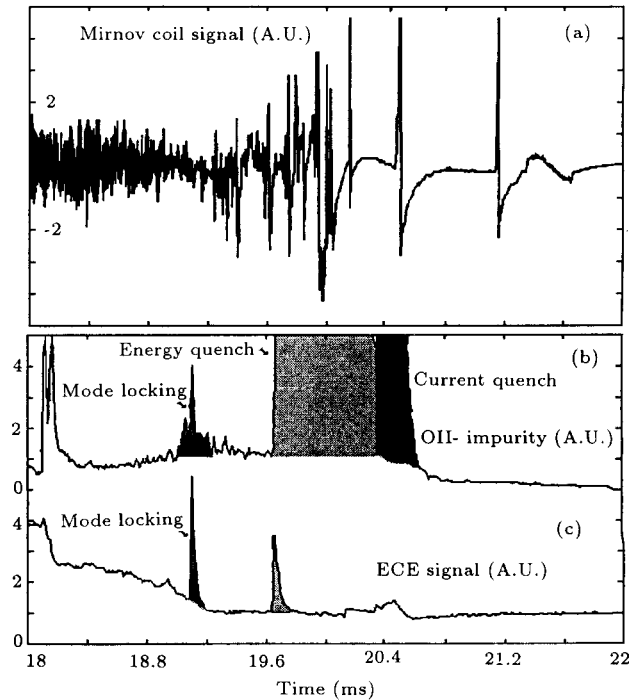


Figure 2. Expanded time intervals of Figure 1; (a) Mirnov coil signals, (b) OII-impurity signals and (c) ECE radiation signals.

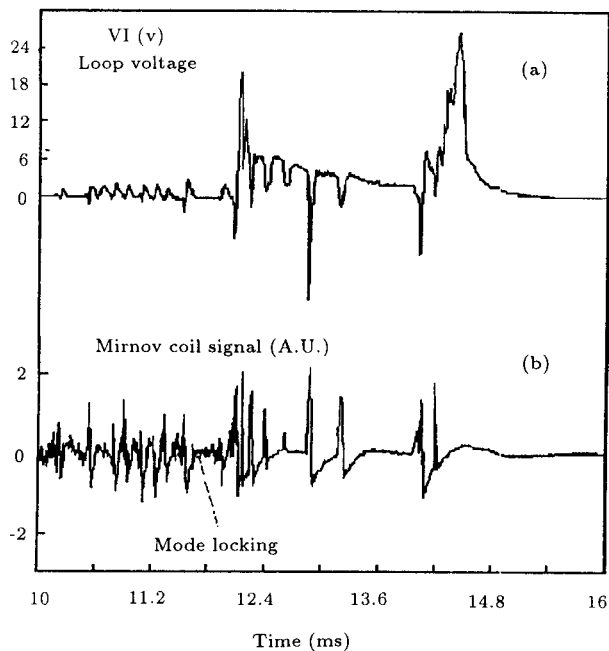


Figure 3. Comparison of the loop voltage signal and Mirnov coil signal at time interval 10-16 ms.

voltage spike. The MHD activity is increased, as shown in Figure 3b, 0.2 ms before the negative spike. These figures clearly show that every negative peak in the loop voltage is accompanied with a peak in the Mirnov signal, which is due to the fluctuation of the radial magnetic field in the disruption phase. A similar process is also observed in [17] which shows the positive vertexes of plasma current accompanied with the peaks of radial magnetic field fluctuation in the disruption phase. The discharge characteristics in the quasi-steady state are dominated by large sawtooth oscillations, which are observed not only in x-ray and ECE signals, but also in the loop voltage as shown in Figure 3. The sawtooth like oscillations observed in the loop voltage in the time interval 10.6-11.6 ms (in the precursor phase of disruption) are due to a re-arrangement of the current distribution. As shown in this figure, the sawtooth oscillations in the loop voltage stopped after the appearance of mode locking at 11.6 ms. After mode locking a negative peak close to 0.4 ms is observed in the loop voltage signal which is a mark of disruption process. Thus, it can be concluded that at least in the condition of our experiment, the appearance of mode locking causes a cessation in sawtooth like oscillations (in the loop voltage signal) which leads to the disruption of plasma current.

It has also been shown that the frequency of Mirnov signal is in agreement with the scaling law of the critical error field which makes us sure that the mode locking process has occurred [18]. To do this the frequency of Mirnov signals before mode locking

Table 1. Comparison of some parameters of COMPASS-C, DIII-D and IR-T1.

	COMPASS-C	DIII-D	IR-T1
R_0	0.56	1.67	0.45
B_t (T)	1.1	1.3	0.7
f (kHz)	13	1.6	21

has been calculated to be about $f = 21$ kHz which is close to that of the electron drift frequency f_D defined by $f_D = K_e T_{eo} / ea^2 B_t$ [19], where K_e is the Boltzman constant and e is the charge of electron. By putting $T_{eo} = 150$ eV the central electron temperature, $B_t = 0.7$ T toroidal magnetic field and $a = 12.5$ cm f_D is found to be 21 kHz. This frequency is also measured experimentally to be about $f = 20$ kHz, which is in agreement with the above calculated frequency. On the other hand this frequency is calculated with a scaling law of the critical error field $f \approx R^{-9/5} \times B_t^{-1/5}$ [18], as shown in Table 1.

CONCLUSION

In this paper, the mode locking behaviors in the IR-T1 tokamak have been studied and mode locking in IR-T1 at safety factor $q(a) = 2.5$ has been shown to occur. The results illustrate that during the precursor phase and before the disruption, the MHD turbulence appears and the oscillation frequency of the magnetic field decreases to about zero. This frequency (before mode locking) is quite in agreement with the scaling law of the critical error field and also with the electron drift frequency. It has also been concluded that, at least, under the conditions of the presented experiment, the appearance of a mode locking causes a cessation in sawtooth oscillation, which in turn leads to a disruption of plasma current. This may let us to predict the disruption and thus to avoid it by a suitable control system.

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