CONTROL OF THE OSCILLATORY REGIME BY LOCAL CURRENT PERTURBATION IN ECCD PLASMAS ON TCV

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1. Introduction

Electron internal transport barriers (eITBs) are routinely obtained in the Tokamak à Configuration Variable (TCV; R/a = 0.88 m/ 0.24 m, $B_T < 1.54$ T) in plasmas with strong Electron Cyclotron Resonance Heating and Current Drive (ECRH/ECCD). In TCV, the key requirement for eITBs is a hollow current density profile, further enhanced by the bootstrap current. These plasmas usually exhibit two types of magnetohydrodynamic (MHD) modes, ranging from ideal (infernal) to resistive (Neoclassical Tearing Modes, or NTMs), which cause negative effects on the confinement. Therefore, development of a technique, which can mitigate the effect of confinement deterioration by MHD activity by local ECCD-induced current density perturbation, is one of the high-priority issues in TCV research programme.

In the paper, studies of the MHD mode evolution in the newly discovered regime with oscillations of the central electron temperature [1] are discussed. MHD activity and reversed magnetic shear are key requirements for the Oscillatory regime (O-regime) to occur on TCV. It is demonstrated that the O-regime can be effectively suppressed (together with MHD activity) by ECCD-induced local current density perturbation. In these experiments MHD activity is modified through current density profile tailoring rather than local deposition within an island. A transition from resistive to ideal type of MHD with increased local pressure gradient in the O-regime will be shown. The nature of the modes appearing in the central region (where the oscillating part of the temperature is located) has been investigated by means of ECE (in particular by the newly installed high-resolution correlation ECE [1]) and magnetic diagnostics, such as Mirnov coils.

2. Experimental conditions

Studies of MHD mode evolution have been performed in fully non-inductive discharges sustained by strong (1 MW and more) off-axis co-ECCD at low density ($\leq 10^{19}$ m^{-3}). These shots feature eITBs, as evidenced by an increase in the energy confinement time enhancement over TCV L-mode scaling (the Rebut-Lallia-Watkins scaling [2]), H_{RLW}, ranging from 2.5 to 4 and even higher. The eITBs are usually sustained for many current diffusion times. The development of the MHD activity may lead to confinement degradation and may trigger the O-regime similar to the one observed on Tore Supra [3, 4]. On TCV, the O-regime is unambiguously linked to the evolution of the MHD instabilities and is characterized by global oscillations (5 – 15 Hz) of the electron temperature and the plasma current. The plausible mechanism of how the evolution of the magnetic island triggers the O-regime is described in [1] and will not be repeated here. It has been demonstrated that oscillations can be effectively suppressed by adding an Ohmic current perturbation with a negative or positive sign, with respect to the direction of the plasma current. In the first case, the MHD mode grows close to the ideal limit and the O-regime is terminated by a minor disruption. The confinement recovers and oscillations do not reappear. In the second case, the O-regime is softly suppressed but MHD remains. It has been shown in [1] that the MHD mode in the O-regime is consistent with NTM characteristics.

3. Suppression of the O-regime by ECCD-induced local current density perturbation

Another way to stabilize the O-regime is to tailor the current density profile by means of co- or counter-ECCD in the plasma center. By adding central (well inside the barrier) co-ECCD (0.25 MW) at 1.5 s in the discharge #33812, the O-regime has been suppressed, although an MHD mode has continued until the end of the plasma (Fig. 1). As the current density becomes less hollow (compared to the phase with oscillations), the barrier loses its strength at 1.6 s (with a delay comparable with the current redistribution time), as proved by a drop in the H_{RLW} from 3 (during the O-regime) down to 2. This corresponds to the change in the energy confinement time from 2 ms down to 1 ms. The MHD mode has been identified as m/n = 3/1 from Mirnov coils and is located at r/a = 0.4 (just outside a foot of the eITB), as confirmed by ECE measurements.

In alternative, it can be demonstrated that getting rid of MHD aids to the suppression of the O-regime even if the transport barrier is preserved. In discharge #33897 (Fig. 2) the total power of co-ECCD off-axis beams has been continuously decreased from 1.5 MW at 1.5 s down to 0.6 MW at 2.2 s. In order to keep the strength of the transport barrier unchanged, counter-ECCD on-axis beam has been added from 1 s to 2.2 s with a constant power of 0.25 MW. Although the off-axis co-driven current decreases, thus raising the value of q_{min}, the inverted central shear condition remains. At 1.7 s, the MHD mode (which is m/n = 3/1 from magnetics) is completely stabilized, as confirmed by the analysis of correlation ECE spectra. At the same time, global plasma oscillations disappear. The energy confinement time enhancement, H_{RLW}, evidently increases its value from 3 to 3.5 after the suppression of the O-regime, indicating that the transport barrier has gained strength.

Interestingly, an evidence for the higher-frequency mode at 35-45 kHz with a bandwidth of several kHz is obtained in discharges with the global plasma oscillations by means of correlation ECE (Fig. 4). This mode is not a harmonic of the lower-frequency m/n = 3/1 mode and does not disappear together with the O-regime. Geodesic Acoustic Modes (GAMs) on TCV (Te/Ti>>1) are calculated to have frequencies in the range between 80 and 140 kHz (depending on the particular plasma conditions), well above the observed values. A possible candidate is the so-called electron fishbone mode which is a marginally stable ideal mode driven by barely trapped non-thermal electrons that may exist near the location of the minimum safety factor in the plasmas with inverted q-profile [4]. For the electron fishbone mode to be destabilized, the existence of an electron population with precession frequency corresponding to the mode frequency is necessary. Indeed, for the mode frequency f = 37 kHz, q = 3, r/a = 0.4 and B_t = 1.4 T, the energy of barely trapped electrons is estimated to be: $E_{eV} \approx 2\pi f\times rR_0\times B_t/q$ = 13 keV. In TCV, the presence of fast electrons with these energies (and higher) has been confirmed by measurements and simulations [1, 5]. However, to identify this mode unambiguously as an electron fishbone, further experiments with the HFS ECR heating, which would drive barely trapped electrons to a higher energy and thus affect the mode frequency, are foreseen.

Also, the presence of the broadband (between 30 - 200 kHz) temperature fluctuations has been found during the phase with oscillations (Fig. 4). These broadband fluctuations do not exist during the Ohmic phase of the discharge (before 0.5 s), and disappear as soon as ECH power drops below a threshold of about 1 MW after 1.7 s. A possible influence of both kinds of modes on the confinement properties has not been yet investigated and will be the subject of a separate study.

4. Transition from the resistive to the ideal type of MHD during the O-regime. Excitation of the O-regime by modulated ECRH

On the top of the slower plasma oscillations, when the local pressure gradients are the largest, relatively small crash-like features are observed. This is an indication of an ideal type MHD which tends to prevent the formation of an eITB. The ideal phase is followed up by a longer resistive phase, as the island grows and flattens the pressure profile. If more heating or counter-ECCD is added inside the barrier (thus increasing its strength), the ideal mode, which is often referred to as an infernal mode [6], can cause big crash-like oscillations resembling sawteeth but involving the region close to q = 3 surface. A transition from sinusoidal-like slow oscillations in the O-regime to crash-like regime is observed if the barrier strength is continuously increased during the discharge. In shot #33813, the plasma parameters were similar to the previously described discharge #33897 but the co-off axis ECCD power was kept constant (Fig. 3a). It can be seen that adding 250 kW counter-ECCD on-axis influences the shape of the oscillations, and finally a minor disruption occurs at 2.4 s. A better example is given by shot #32028, in which the transition through the O-regime into the crash-like regime (also called Periodic Relaxation Oscillations regime, or PRO, in TCV [7]) is observed at 1 – 1.1 s (Fig. 3b). In this shot, the barrier has been created by 1 MW off-axis co-ECCD and 0.5 MW ECRH inside the barrier plus Ohmic current contribution, compared to 1 MW of co-ECCD only in previously discussed fully non-inductive discharges.

The O-regime can be triggered artificially if modulated ECRH power (10 Hz, 0.5 MW) is added inside the barrier, after it has been sustained by 1 MW off-axis co-ECCD (Fig. 5). The MHD mode frequency dynamics follow these “induced” oscillations. Interestingly, when the artificial modulation is finished and ECRH power inside the barrier remains constant, natural oscillations (the O-regime) continue with the same frequency (10 Hz).

These experiments have shown that even a slight change in the plasma parameters in reversed-shear scenarios with large pressure gradients may lead to the significant change in the MHD mode character and trigger non-linear regimes, such as global plasma oscillations and/or PROs.

5. Conclusions

It has been demonstrated that local current perturbation by ECCD can suppress the O-regime and recover eITB with higher H-factor. This is achieved by stabilization of the MHD mode via current density profile tailoring and/or modification of the magnetic shear near the q-profile inversion. The transition from resistive to ideal type of MHD mode during oscillatory regime has been shown. A general model that would describe the interplay between MHD activity, current density profile and pressure profile in the O-regime is currently under development.

References

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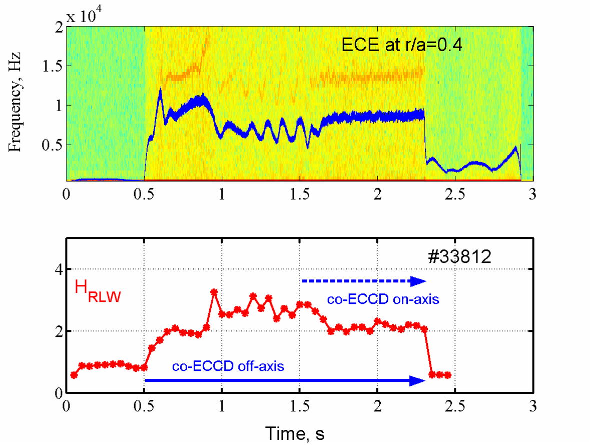

FIGURE 1. Suppression of the O-regime at 1.6 s by adding 0.25 MW co-ECCD on-axis. MHD activity continues until the termination of the discharge.

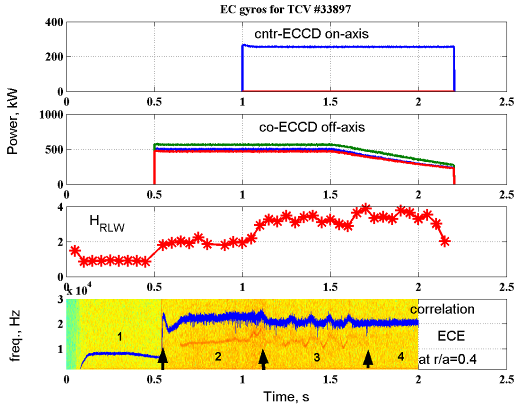

FIGURE 2. Suppression of the O-regime by stabilizing m/n=3/1 mode at 1.7 s (shot #33897). Top: ECH power and H-factor evolution during the discharge. Bottom: correlation ECE spectrogram for the channel at r/a = 0.4. See FIGURE 5 for further details.

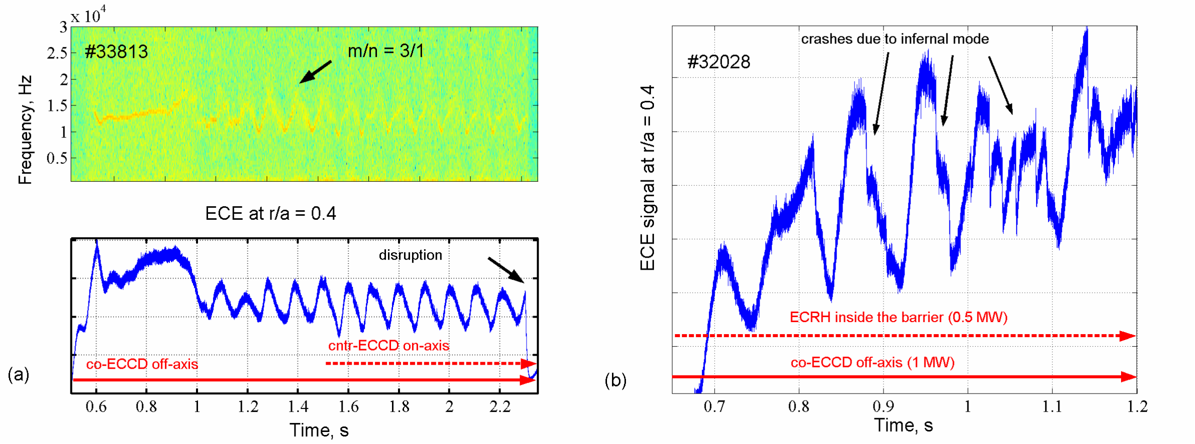

FIGURE 3. (a): influence of additional cntr-ECCD on-axis on the oscillations shape; (b): if more power is added inside the barrier, a transition to the PRO-regime can occur (at 1s).

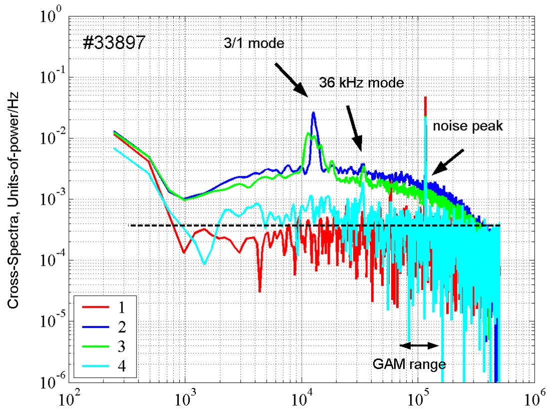

FIGURE 4. Correlation ECE cross-spectra for different time windows (marked 1 through 4; see FIGURE 2) in the shot #33897.

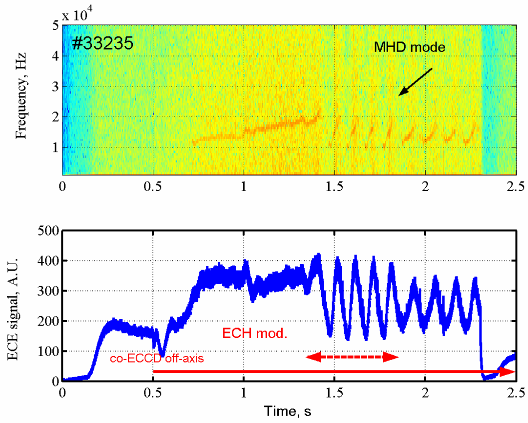

FIGURE 5. Excitation of the O-regime by modulated ECH power (0.5 MW) inside the barrier. The “real” O-regime continues after the modulation stops at 1.8 s.