Mode Coupling Trigger of Tearing Modes in ECW Heated Discharges in FTU Tokamak

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Abstract. In recent ECRH experiments on FTU tokamak the destabilization of (2,1) tearing modes, coupled to the (1,1) mode, has been observed. The dynamics of the rotating island can be described by a Rutherford-type equation, where mode coupling, inertial effects and resistive walls effects are included. TM dynamics is influenced by the position of the absorbing layer with respect to the island, to the extent that the mode can be completely suppressed if absorption occurs at the island radial position, with a precision in the order of the island size. EC absorption leading to TM stabilization is localized on the island by mechanical steering of the EC beam, and not by adjusting the toroidal field or forcing the plasma column in the right position for stabilization. Stabilization is achieved at a minimum ECRH power of ≈0.15 P_{OH}.TM stabilization improves significantly the energy confinement in the plasma core.

1. Introduction

Neoclassical tearing mode control is an important issue in fusion relevant tokamak devices, mostly in view of the negative impact these modes have on plasma stability and energy confinement. Although important achievements have already been reported on active NTM stabilization by LHCD [1] and ECCD [2], still a reliable and automatic system of mode detection/suppression is a challenging realization. ECRH/ECCD is an attractive actuator for a closed loop stabilizing feedback because of the high localization of induced (resistively or EC-driven) control currents, but so far the correct positioning of the absorption layer has been achieved by ramping the toroidal field, which is not a viable solution for useful applications. In this paper we report of experiments on FTU tokamak where Tearing Modes were suppressed by aiming the EC beams on the MHD island, thereby adjusting the control system to the unstable plasma, and not vice versa.

The dynamic behaviour of tightly coupled modes under the influence of ECRH [3] is also discussed in this paper, since the presence of many modes, each one linked to all the others, could be a further difficulty in an automatic stabilization process. At least, the driving mode has to be identified before attempting stabilization.

Finally, it is shown that the mode must be kept rotating, or it has to be unlocked, in order to be stabilized.

2. TM destabilization and coupled mode dynamics during ECRH

An ECRH system at 140 GHz [4], delivering up to 2 MW by 4 gyrotrons with a maximum pulse length of 0.5 s, is used on FTU tokamak for plasma shaping, MHD control and thermal confinement studies. The EC wave antenna is composed by four mirrors, each one illuminating the plasma with a gaussian beam, polarized for optimum coupling to the O-mode. Each mirror is independently steerable both in the vertical (poloidal) and in the horizontal (toroidal) directions. The diameter of the beam in vacuum is ≈3 cm, corresponding to ≈a/10, providing an absorption layer size of the same magnitude. The beam steering capability has been used to study the effect of the current density profile shaping at fixed plasma current and q_a, on the MHD activity and TM mode dynamics.

Absorption of 400 kW of EC power at $r_{inv}<r_{abs}\approx 0.3a$, r_{inv} being the sawtooth inversion radius, may lead in discharges with Ip=400 kA, $q_a\approx 7$, at sawtooth suppression and destabilization of an m=2,n=1 tearing mode. After sawtooth stabilization, the (2,1) mode couples to a more central (1,1) mode, so that thermal oscillations determined by the presence of these MHD instabilities occur at all radii strictly at the same frequency.

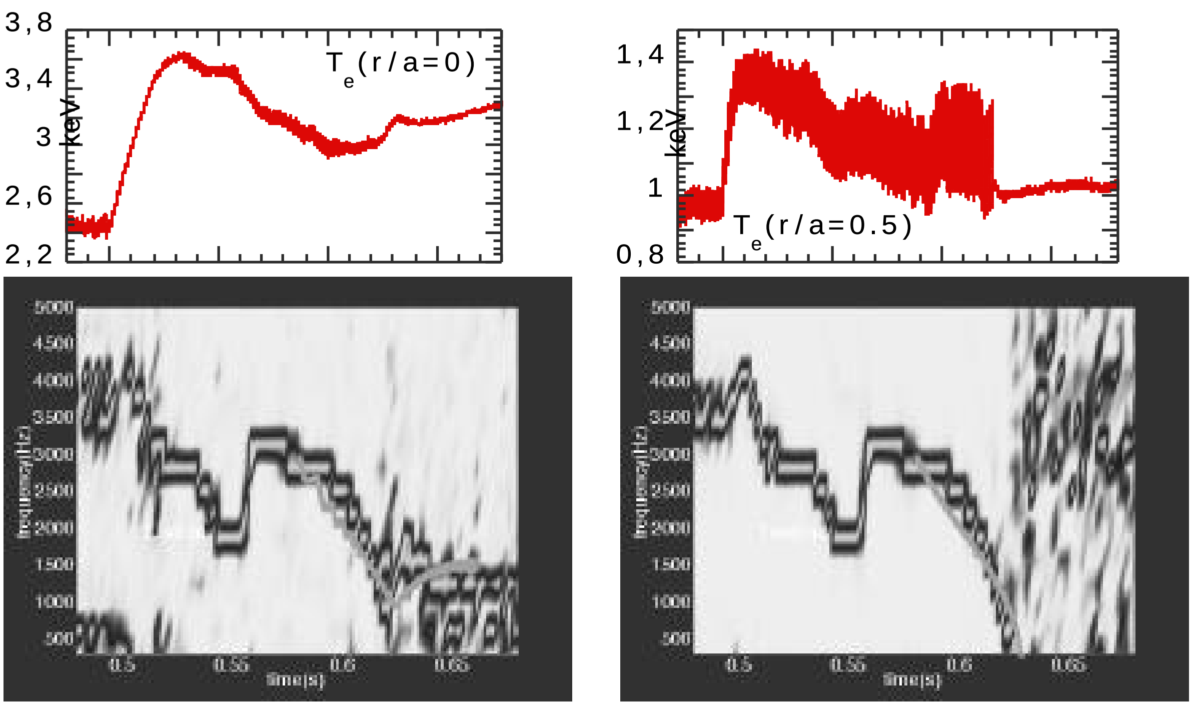
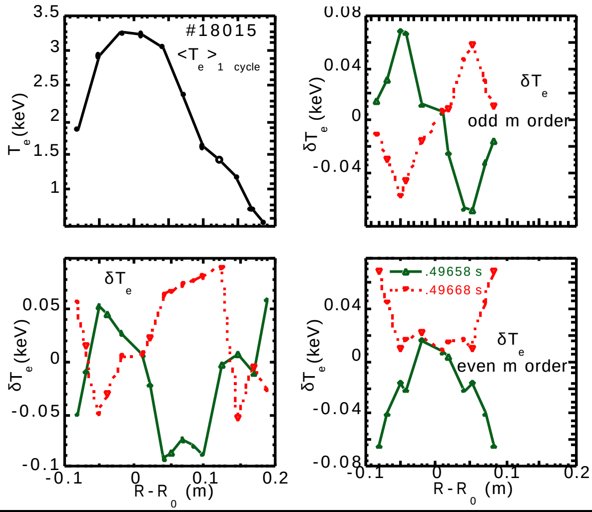


FIG.1 The figure shows the time dependence of the electron temperature $T_{e,ECE}$ (top) measured at different radii in a plasma affected by coupled (2,1) and (1,1) tearing modes, and of the frequency spectrum (bottom) of the associated temperature fluctuations. All the elements governing the island dynamics appear to be active: current density gradient and pressure gradient, eddy currents in resistive walls (leading to mode locking), mode coupling, viscosity and island inertia. The thick grey curve is the estimate of the frequency dependence based on a Rutherford type model of mode dynamics including all relevant terms.



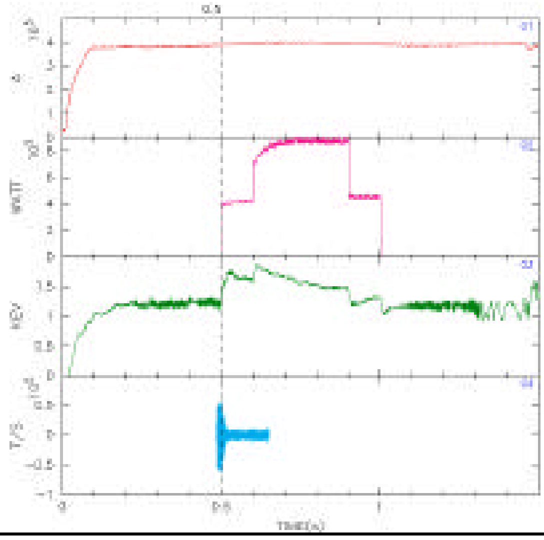


Fig.2 Radial profile of electron temperature (top-left) fluctuations (bottom-left) shows that an odd mode (top-right), central, and an even mode (bottom-right) coexist. The two modes are tightly linked, their frequency being exactly the same.	*Fig.3 Shot #18015, top to bottom: plasma current, ECRH power, $T_{e.ECE}$ at half radius, Mirnov coil signal (limited by DAS memory). ECRH, applied by beam steering at $r_{abs/a}$=0.52, suppresses MHD instabilities and the associated thermal fluctuations.*

It may happen that the (2,1) mode grows and eventually locks because of wall braking effects, and in that case (1,1) may be freed by viscosity friction forces and continues rotation at its natural frequency. All these features can be found in Fig.1, where the time dependence of the electron temperature at r/a≈0.1, where (1,1) mode mostly determines thermal fluctuations, and at r/a≈0.5, close to $r_{q=2}$, are shown. ECRH, starting at 0.5 s, suppresses sawteeth in the plasma core, and contemporarily destabilizes a pre-existing, low amplitude (2,1) TM. After sawtooth suppression and TM destabilization, a (1,1) instability is excited in the central part of the plasma column as an m-1 sideband by toroidal coupling. The time dependence of the frequency spectrum clearly shows that the two modes rotate strictly linked one to the other. The complex dynamics of the two modes is the result of the balance between mode to mode coupling effects, viscosity effects which tend to keep the modes rotating at their own natural frequency, and interaction with eddy currents in the resistive wall, which tend to slow down mode rotation (wall effects are mostly effective on the outer m=2,n=1 mode, but are much weaker on the inner, m=1;n=1 mode).

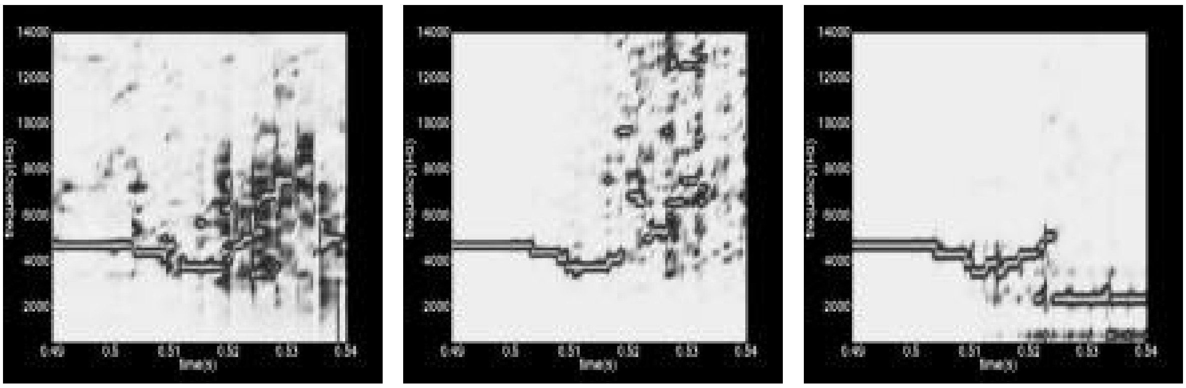


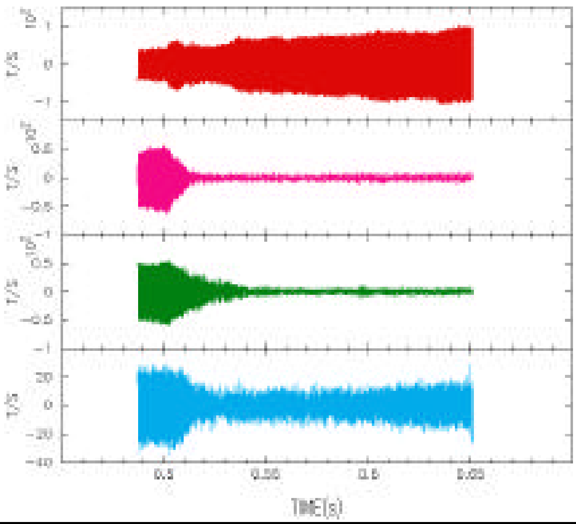
Fig.4 From left to right: frequency spectrum of thermal fluctuations at center, due to (1,1) MHD instability; at ≈a/2, caused by (2,1) tearing mode; of external magnetic fluctuations. All spectra are normalized at Max=1. Coherent temperature oscillations, strictly at the same frequency at all radii, vanish after ≈26 ms from ECRH start at 0.5 s. The residual signal on the Mirnov coils after mode stabilization is spurious.

Varying inertia, due to the island growth, contributes to the effective time dependence of the rotation frequency. After a few jumps, likely between the natural frequencies of the two modes, rotation is finally stopped, (2,1) mode locks to the walls while the (1,1) mode, too far from the wall, slips away and freely continues rotation.

An interpretation of the observed behaviour can be given through a nonlinear dynamic model for the evolution of the island width and rotation frequency. By extending the procedure introduced by Rutherford for large R/a and RHMD ordering [3 and references herein], a system of coupled equations for the mode amplitudes and rotation frequencies is obtained. After the turn on of the ECRH power and the suppression of sawteeth oscillations, plasma pressure P increases and q profile changes in a way that $\beta_p = P \big/ 8\pi B_\theta^2$ increases above the critical value for which the destabilizing contribution, due to the flattening of the bootstrap current across the initial island, overcomes stabilizing terms. This leads to (2,1) destabilization, followed by (1,1) excitation. From that time on, and in particular during the slowing down phase leading to wall locking, the nonlinear modelling describes satisfactorily amplitude [3] and frequency evolution of both (2,1) and (1,1) modes (Fig.1).

3. TM stabilization by ECRH

A different situation is found sometimes, depending on specific conditions in the current ramp-up phase up to the plateau value of 400 kA, that at the time of turning ECRH on sawteeth are already absent, and the (2,1) mode is already fully developed.



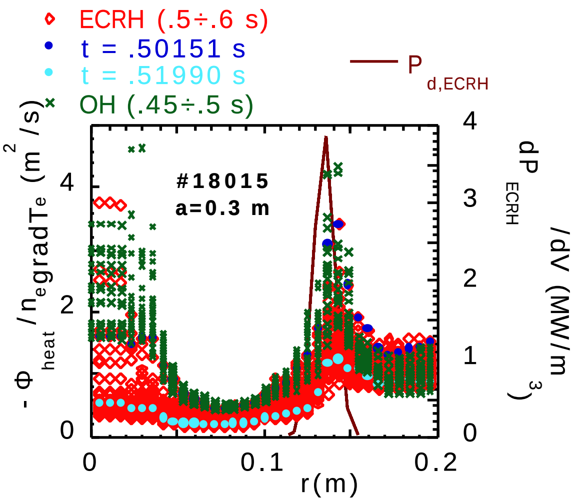
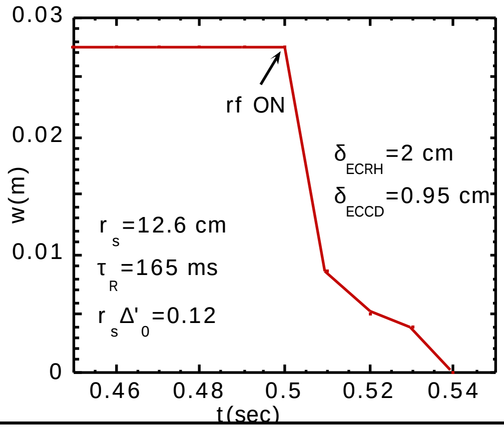


Fig.5 Mirnov oscillations with different values of $\delta R = R_{abs} - R_{O\text{-}point}$. ECRH starts at 0.5 s. From top to bottom: δR=-3 cm, 0, +1 cm and +2 cm.	Fig.6 $\chi_{e,eff}$ vs. minor radius in the ohmic phase (green x) and during TM stabilization (red diamonds). ECRH profile closely overlaps the island (high $\chi_{e,eff}$ region at 0.14 m).

An analysis of the current density and pressure profiles shows that in this case the instability parameter $r_{s_{q=2}} \Delta'_J$ is not largely negative (≈-1), and that the destabilizing contribution coming from boostrap current flattening brings the plasma to be unstable for m=2,n=1 MHD instability. It happens therefore that in a marginally unstable plasma, neoclassical effects strongly contribute to the mode saturated amplitude. Also in these plasmas an m=1,n=1 is excited by toroidal coupling. As shown in Fig.2, the radial profile of δT_e fluctuations, taken at instants of minimum and maximum temperature at a given point in the plasma, can be splitted into its even (m parity) component, which is larger near half



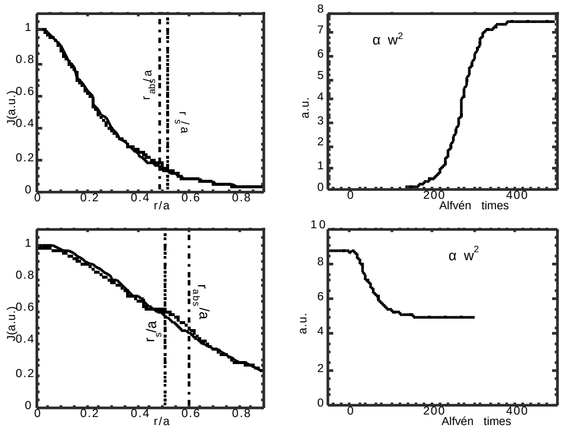


Fig.7 Island width evolution estimated by using a Rutherford type relation between growth rate and stabilizing/destabilizing factors, including the term due to EC induced helical currents (by heating and current drive). Key parameters are equal to the experimental values. Estimate is close to experiment.

Fig.8 Estimate of the island width evolution determined by a local symmetric perturbation of the current density profile, close to the one expected during experiments on TM control with ECRH. It shows that Δ' changes may contribute to TM suppression, in addition to helical currents effects.

radius, and its odd part, concentrated close to the plasma center. There are therefore at least two modes which coexist in the ohmic phase, tightly coupled since the frequency of thermal oscillation is strictly the same at all radii, up to well outside half radius. By looking at the width of the annular region where the T_e profile is flattened by the high heat transport across the island, it turns out that its width is w ≈ 3 cm ≈ a/10. The presence of TM is also detected by external Mirnov coils coupled to the varying poloidal field. The amplitude of the measured poloidal flux fluctuations due to a rotating (2,1) island is, consistently with thermal estimates, w=2.94 cm at ECRH turning on.

In these conditions the island dynamics is heavily affected by the position of the ECW absorbing layer, to the extent that the (2,1) mode can be completely suppressed by ECRH. Fig.3 shows that both thermal fluctuations at r/a≈2, and external Mirnov oscillations disappear after turning on 400 kW of ECRH power (perpendicular injection) in a 400 kA discharge, q_a≈7, ne≈4 10^{20} m^{-3}, P_{OH}≈600 kW. A more detailed description of the events is found in Fig.4, showing the evolution in time of the frequency spectrum of thermal fluctuations close to center at r/a≈0.1 (1,1), at r/a≈0.5 and of Mirnov oscillations. Spectra are normalized to Max=1 at all times. Before ECRH (turn on time: 0.5 s) one single frequency is detected because the two modes are strongly coupled. A single frequency continues, and mode coupling as well, for 26 ms more at all radii, but after that time no coherent thermal oscillations are found any more. The single frequency still present in the Mirnov coil is due to a spurious signal, not to be considered.

TM stabilization is very sensitive to the position of the absorbing layer. It is achieved if the ECW absorption is localized well inside the island, in the center or the flat region on the T_e profile around a/2. As shown in Fig.5, destabilization is, on the contrary, excited if absorption is inside the MHD island, towards the plasma axis. By moving absorption outside the island, towards the edge, the mode is reduced, but not stabilized. It has to be noted that the width δ_{abs} of the power deposition profile is ≈ 3 cm, almost equal to the island saturated amplitude w, so that localization sensitivity is ≈ δ_{abs} ≈w. This is shown in Fig.6, where the power deposition profile, as estimated by ray tracing calculations, is compared with the region of high electron thermal diffusivity, coincident with the MHD island. As mentioned before, it is important to note that correct positioning of the absorbing point well inside the island, at its O-point, is achieved by a vertical steering of the EC beam, and not by adjusting the toroidal magnetic field.

Two are the possible processes leading to TM mode suppression by localized ECRH/ECCD. According to the first one, by heating inside the island the reduction in resistivity accumulates there an helical current which tends to cancel the current density perturbations associated to the TM. It has been shown [5] that, if the island rotates, stabilizing current build-up at the O-point is more effective than the destabilizing accumulation at the X-point. Such a scheme can be implemented into the nonlinear model for the island growth rate and rotation speed, by an appropriate Δ' contribution [6]. This has been done, taking into account all the relevant plasma parameters and ECRH conditions of the discharge where stabilization was achieved starting from a saturated island ≈a/10 wide:

$$\frac{dW_m}{dt} = \frac{r_{s,m}^2}{\tilde{\tau}_{R_m}}\left[\Delta'_{0m} + \Delta'_{boot} - \Delta'_{GGJ} - \Delta'_{\kappa,\delta} - \Delta'_{pol} - \Delta'_{ECRH} - \Delta'_{ECCD}\right]$$

where $\Delta'_{\kappa,\delta}$ is the cross-section shape stabilizing term, Δ'_{ECRH} is the ECW stabilizing term due to heating, and Δ'_{ECCD} is the stabilizing term due to current drive. An excellent agreement with the experimental results was found. As shown in Fig.7, the island drops to a negligible fraction in times well in agreement with observation. It should be noted that, since alignment on the island was achieved by steering the beam outside the equatorial plane, this means that some amount of ECCD was driven also in the case of perpendicular launch because of the poloidal magnetic field. ECCD term is included in the model and, although small, it still contributes to the dynamics even if it is marginal for stabilization. In the conditions of the experiment, the stabilizing term due to resistive current density accumulation $|\Delta'_{ECRH}|$ is much stronger than the equivalent term due to direct current drive $|\Delta'_{ECCD}|$.

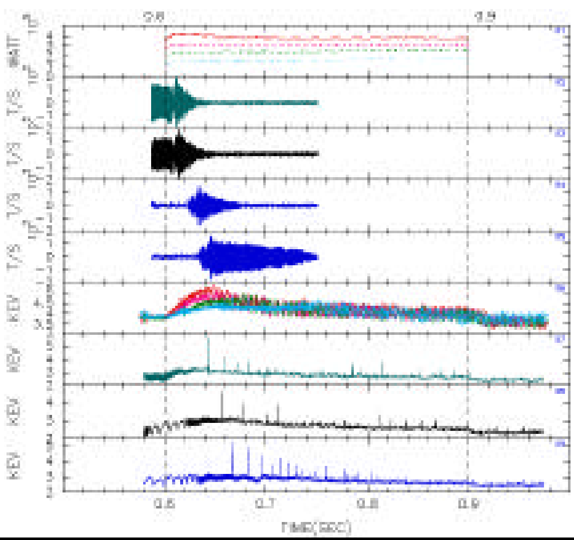


Fig.9 Top to bottom: P_{ECRH} (370, 315, 250 and 165 kW); Mirnov oscillations; central T_e (all cases); T_e at r≈a/2 for the last 3 cases (315, 250 and 165 kW).

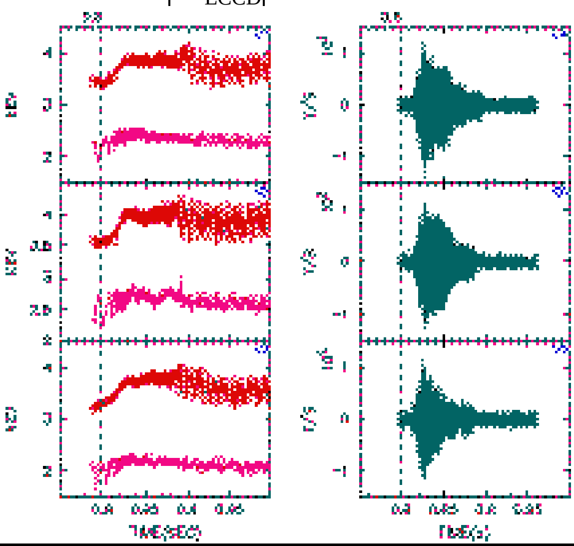


Fig.10 T_e at center and at r≈a/2 (left), and Mirnov oscillations (right) with co-ECCD injection (top), counter injection (bottom), and perpendicular launch (center).

A second process, also verified in experiments [1], rely on the local perturbations on the current density profile, symmetric with respect to the magnetic axis, which directly affect the destabilizing term Δ'_J. The effect is shown in Fig.8, where plasma parameters and heating conditions consistent with the experimental ones are considered. If absorption, heating and current density profile modification are localized internal to the q=2 resonant surface, a stable profile is turned unstable. This is perfectly consistent with experimental findings. If absorption is outside the resonant surface, the amplitude of a pre-esxisting mode is reduced, and this also is a feature well in line with experiments. It turns out therefore that TM mode stabilization could be obtained by optimizing both processes, although the one relying on O-point absorption is likely more efficient for full TM suppression.

An important consequence, implied by both processes, is that the mode is much more efficiently stabilized is the island rotates, and this in fact corresponds very well to experiments. Fig.9 shows, amongst the others, two discharges in which the island is almost stationary when ECRH is turned on. From T_e oscillations at a/2, almost constant when the island rotates with a period much longer than thermal diffusion time across the island, it is quite clear that the amplitude does not decrease with ECRH. Only when spinning starts again, also the stabilization process starts.

An important aspect of TM stabilization for fusion applications is the assesment of the minimum power needed. A power scan has been performed on FTU to identify the minimum requirement for TM stabilization in a 400 kA, P_{OH}=600 kW, discharge, which has been found to be $P_{threshold} \approx 0.15\ P_{OH}$. Although the minimum power requirement very likely depend on the specific situation, on the strength of the destabilizing forces, on the type of mode, on the presence of coupled modes, and so on, the threshold found in FTU is well in line with observations from very different experiments.

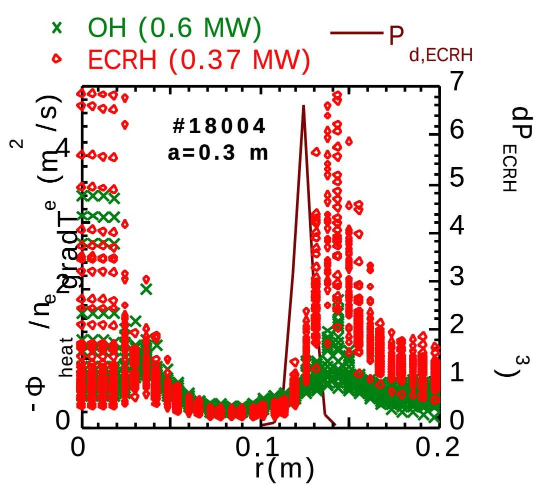


Fig.11 $\chi_{e,eff}$ *vs. minor radius in the ohmic phase (green x) and during ECRH (red diamonds). ECRH profile is shifted 3 cm inward with respect to the island (high* $\chi_{e,eff}$ *region at 0.14 m). In this case TM is further destabilized and the island width is further increased.*

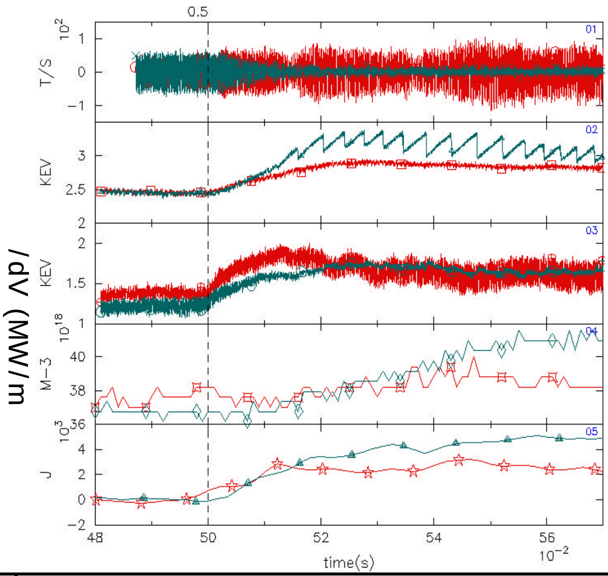


Fig.12 Shot #18004 and #18015 are compared. In #18004 absorption is at $r_{abs}/a=0.46$*, 3 cm and stabilization fails. Top to bottom: Mirnov signals,* $T_{e.ECE}$ *at center and half radius, central line density, global energy increase. Core confinement improves with TM stabilization.*

4. ECCD contribution to ECRH

More efficiently than ECRH, ECCD is expected either to compensate for helical currents or to locally modify the global current density profile. As a matter of fact, resistive current density accumulation is effective already at moderate electron temperatures, provided that the plasma is optically thick at the island position. The effect is quickly saturated as T_e is increased. On the contrary, ECCD efficiency increases with electron temperature, and the efficiency of TM stabilization by ECCD is expected to increase with temperature. In fact, experiments performed on FTU at moderate T_e show that the CD contribution to stabilization is marginal, if at all present.

Fig.10 shows that stabilization with co and counter ECCD is identical to the one achieved with perpendicular launch, provided that the absorption radius is the same in all cases. As expected, heating is dominant in this case over current drive.

5. Effects on confinement

The beneficial effects of mode suppression on energy confinement are shown in Fig.12, where two discharges are compared, which are almost identical in the ohmic phase, but with ECRH absorption occurring in slightly different positions. In shot #18004 absorption is ≈3 cm internal to the island O-point, as shown in Fig.11. As already mentioned, and shown in Fig.11, m=2,n=1 mode is eventually destabilized in this case. In shot #18015 EC absorption is correctly positioned inside the island, and stabilization occurs on the expected resistive time scale. All central parameters (temperature, density, stored energy) do increase in the same way in the two shots until TM stabilization is almost fully achieved. From that time on, a much better thermal and particle confinement characterizes the stabilized plasma. In stationary conditions the increase in stored energy is twice higher in the stable, #18015 discharge than in still unstable #18004 shot. In #18015 the improvement in core confinement and T_e peaking causes the appearance of sawteeth and the transition to a different regime.

6. Conclusions

Experiments on TM stabilization with ECRH on FTU tokamak confirm that a condition necessary for mode stabilization is the precise alignment of the absorption on the island O-point, and demonstrate that this can be achieved by steering the EC beams, at constant $B_{toroidal}$ and plasma current.

It is shown that mode coupling, in case of many modes coexistence, is important in choosing the most effective stabilizing procedure, since mode dynamics is strongly affected by ECRH.

In particular, the mode to be stabilized, whether it is alone or coupled to other modes, should be made rotating before attempting stabilization.

The experiments confirm that a relatively low fraction of the ohmic power is sufficient for stabilization, and that the gain in core confinement after TM stabilization can be very significant.

References

[1] C D Warrick et al., Phys. Rev. Lett. **85** (2000) 574.

[2] Gantenbein et al., Phys. Rev. Lett. **85** (2000) 1243

[3] E.Lazzaro et al., Phys. Rev. Lett. **84** (2000) 6038

[4] C.Sozzi et al., 13th Topical Conference on Radio Frequency Power in Plasmas, Annapolis, 1999, pp. 462-465

[5] H.Zohm, Phys. Plasmas **4** (1997) 2940

[6] G.Ramponi, E.Lazzaro, S.Nowak, Phys. Plasmas **6** (1999) 3561