Global Plasma Oscillations in Electron Internal Transport Barriers in TCV

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Abstract

Global plasma oscillations have been observed in the Tokamak à Configuration Variable (TCV; R/a=0.88m/0.25m, B_T<1.54T) in reversed magnetic shear discharges (fully non-inductive driven) with electron Internal Transport Barriers (eITBs). These slow oscillations involve the electron temperature and density and the plasma current. The triggering mechanism is the periodic destabilisation and stabilisation of a magnetic island near the foot of the barrier. The regime observed on TCV is due to the large pressure gradients in a region of low magnetic shear, typical in eITB plasmas. Depending on the proximity to the marginal ideal infernal stability limit, the phenomenology of the mode can exhibit more ideal-like (minor or major disruptions) or resistive-like behaviour. Regardless of the character, the result is a reduction of the confinement, a lowering of the electron pressure and thus a decrease of the bootstrap current. These fully non-inductive discharges have large bootstrap fraction; therefore, the total plasma current is affected. Due to the proximity to the marginal stability limit, the modes can be stabilised by the changes in the pressure gradient and local q profile induced by the MHD. This results in a recovery of good confinement properties with the re-establishment of the internal transport barrier, and the cycle can begin again.

The oscillations can be controlled by modifying the current density or the pressure profiles, either with Ohmic current density perturbations or by means of localised RF heating and current deposition. Results from transport simulations are used to show how the mechanism involved in the development of global oscillations through the periodic stabilisation-destabilisation of resistive MHD can be linked to the observed modifications of the pressure profile.

I. Introduction

Global periodic plasma oscillations have been observed in the Tokamak à Configuration Variable (TCV; R/a = 0.88 m/0.25 m, B_T < 1.54 T, [1]). These phenomena can be referred to as global due to the experimental evidence which accompanies it. Indeed, the oscillations are seen to affect the plasma current, electron temperature and density (therefore the SXR radiation emission) among other plasma parameters. The oscillations are invariably linked to the creation of an electron Internal Transport Barrier (eITB) which is obtained thanks to the employment of up to 6 gyrotrons (each one capable of 500kW injection power, operating at the second harmonic of the electron cyclotron resonance). The gyrotrons are used in different combinations to provide pure heating (ECRH) and/or non-inductively driven current (ECCD).

A reverse shear plasma is necessary for the formation of eITB in TCV [2,3], and this is obtained through ECCD and with the help of the bootstrap current. In order to tailor the current profile to create an eITB [4,2], co-ECCD off-axis or counter-ECCD on axis can be used, in addition to central heating. Fully non-inductive barriers are routinely created with one of the two mentioned strategies. Depending on the formation scheme and, combination of current density and pressure profiles can lead or not to MagnetoHydroDynamic (MHD) activity [5,6].

The MHD activity is always detrimental for the confinement properties, and even more so in the presence of an eITB. Indeed, in this case the effect of the MHD activity is of decreasing the strength of the eITB, with consequent loss of confinement and, in the more virulent case, the possibility to reach a disruption. If the MHD activity is located in the region of the foot of the internal transport barrier [6] then the enhanced transport can cause an erosion of the barrier itself, which results in a diminished slope of the barrier and a loss of electron temperature and density in the core.

Advanced scenarios featuring eITBs in TCV lead to the co-existence of a low magnetic-shear and strong pressure gradients in the same region, that of the foot of the barrier (where the minimum of the safety factor q is located [2]). This is a region where the ß-limit is reduced by the so-called ideal infernal stability limit [7, 8], for which the combination of low, rational q surface in the region of low-shear acts to diminished the typical $ß_N$ stability criterion (Troyon limit, [9]).

Depending on the closeness to the ideal infernal stability limit, the MHD developing in the region of low shear can exhibit a more ideal or resistive behaviour. Examples of the first type are q=2 sawteeth [10,11], ß-collapse [12], minor and major disruptions [8]. Resistive MHD in the region of the foot of the barrier can cause the so called O-regime [13, 5, 6], with slow (~10Hz) sinusoidal-like global oscillations of the plasma.

Regardless of the character of the MHD, the instability lowers the electron pressure; thereby decreasing the bootstrap current density [5,14]. Owing to the fact that the bootstrap fraction is generally 40-50% of the total current, this affects the plasma current as a whole. Due to the changes induced by the MHD mode and the proximity to the marginal stability boundary, the growth of the mode can cause the subsequent self-stabilisation due to the profiles changing towards a more stable state.

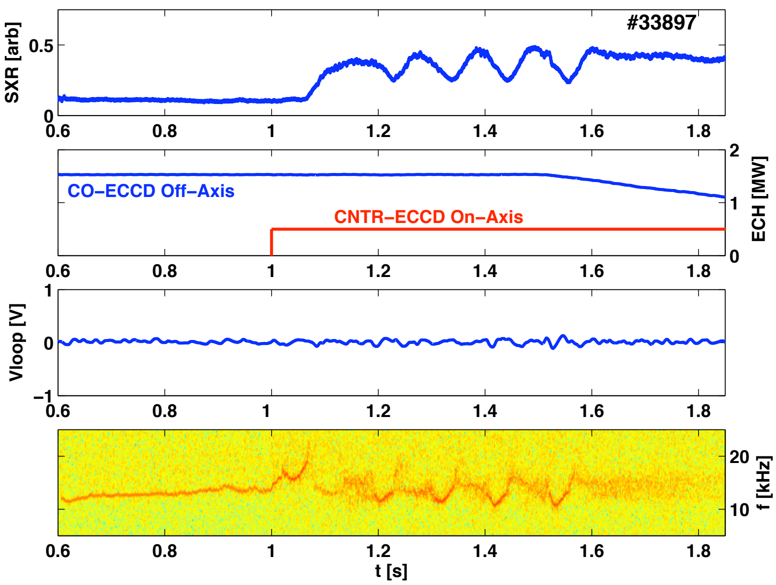

FIGURE 1. *(a) Evolution of the main plasma parameters in fully non-inductive discharge #33897. The top trace is core SXR, which indicates the barrier formation (t=1.08s) and the onset of the global oscillations (t=1.2 s). The combination of co and counter-ECCD is displayed in the second plot. The* v_{loop} *(bottom trace) shows the plasma is fully non inductive and the bottom trace shows the spectrogram of Mirnov probe signal.*

Tokamak advanced steady-state scenarios inevitably involve a rather low shear in a region of strong pressure gradients. In most cases, the ingredients are a strong bootstrap fraction, large pressure gradients and low magnetic shear, i.e. the factors that destabilise infernal modes. Due to the large contribution of the neoclassical bootstrap current, it is very difficult to control them by means of external induced currents (Ohmic and/or non-inductive), unless a

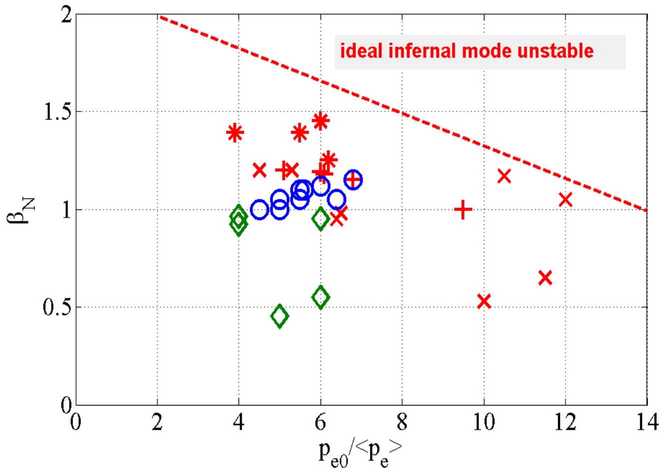

FIGURE 2. *Measured β_N versus the pressure peaking factor, $p_e(0)/<p_e>$ for discharges featuring global plasma oscillations caused by ideal MHD (red marks; "*" are for shots close to a major disruption, "X" are for shots with periodic crash-like global oscillations, "+" are for small fast crashes with amplitude $\Delta T_e/<T_e>$ < 20%), resistive MHD (blue circles) and discharges with MHD activity but without global oscillations (green diamonds).*

loss of the barrier is accepted. TCV has demonstrated in previous publications [5,6], that sinusoidal-like global plasma oscillations caused by resistive MHD can be effectively suppressed by adding co- or counter-Ohmic current perturbations, although the final states depend on the adopted technique. More recently [15], stabilisation of global plasma oscillations regime has been demonstrated via current profile modifications by means of localised ECRH/ECCD.

The mechanism at play in the oscillation regimes in TCV [6] can be modelled, starting from experimental profiles and using transport codes. Preliminary results of the modelling show that an enhanced transport in the region of the foot of the barrier over a width similar to the island width (crude simulation of a magnetic island) can be responsible alone for the reduced strength of the barrier and loss of core pressure.

This paper is organised as follows. The scenarios featuring the global plasma oscillations regime are described in section II. Section III describes the techniques used to stabilise or mitigate the global oscillations. Section IV describes ongoing work in the characterisation of the MHD that is responsible for the O-regime modelling with ASTRA [16].

II. Experimental conditions

Global oscillations develop in TCV plasmas in advanced scenario plasmas. In previous publications, both fully non-inductive and ECCD+Ohmic cases have been described [5,6] underlying the common physical background and the specificity of the MHD triggering the oscillations. Transport code modelling has also confirmed that the current profile, and therefore the safety factor, are compatible with a rational q value appearing in the region of large pressure gradients [3].

One common feature of the plasmas displaying oscillations is that they are always accompanied by MHD activity [5,6]. Depending on the closeness to the marginal ideal infernal stability boundary (fig. 2), MHD modes with resistive or ideal character can be the cause of global oscillations. The plot in figure 2 underlines the fact that increasing the pressure peaking factor (abscissa in fig.2) induces a reduction in the maximum achievable β_N, due to the marginal infernal stability limit [5, 8, 15]. Thus, various types of MHD phenomena observed in reversed shear plasmas can all be ascribed to the infernal stability limit violation, i.e. the *local* destabilising interaction of low magnetic shear and strong pressure gradients which affects the plasma *globally*.

II.I Resistive MHD triggered global oscillations

As an example of resistive MHD triggered global oscillations, discharge #33897 (Fig. 1) is described. This is characterised by 1.35 MW EC power injected from t=0.5 s as off-axis co-ECCD and 0.45 MW on-axis with slight counter-CD component (at t=1.5 s). The eITB formation is confirmed by SXR (top trace, left plot) and by the calculation of the H_{RLW} $(=\tau_{eE}/\tau_{RLW})$ factor, above 3 (TCV L-mode confinement follows the Rebut-Lallia-Watkins scaling [17]). The eITB is sustained for many current diffusion times and is terminated by the limitation in the gyrotrons pulse length. At about t=1.2 s a low frequency MHD mode (12 kHz) is triggered and starts the oscillating part of the discharge. Later, at t=1.5 s, the off-axis power is slowly reduced which inhibits the triggering of this 12 kHz mode and thus stops the global oscillations.

According to MHD analysis, the 12 kHz mode is a magnetic island at the foot of the barrier with a full width that is approximately 5 to 6 cm (tomography and Mirnov analysis). The increased radial transport leads a decrease in the pressure gradient and bootstrap current. Due to the changed stability conditions (lower pressure gradient, higher q_{min} i.e. a more stable plasma), the island self-stabilizes causing the pressure profile to build up again until a new cycle begins. This mechanism for the development of global oscillations due to a resistive mode is described in ref. [5,14] and preliminary results with ASTRA simulating this mechanism are shown in section IV.

The achievable β_N [8,14,15] decreases with the pressure peaking factor and the closeness to a rational low q_{min} (for the analysed cases either q_{min}=2 or 3, fig. 2), and increases with the radial location of the q_{min} and the width of the eITB . When extra heating or counter-ECCD is applied inside an existing barrier (thus increasing β_N and the pressure peaking factor, $p_e(0)/\langle p_e\rangle$), the ideal infernal mode can become unstable.

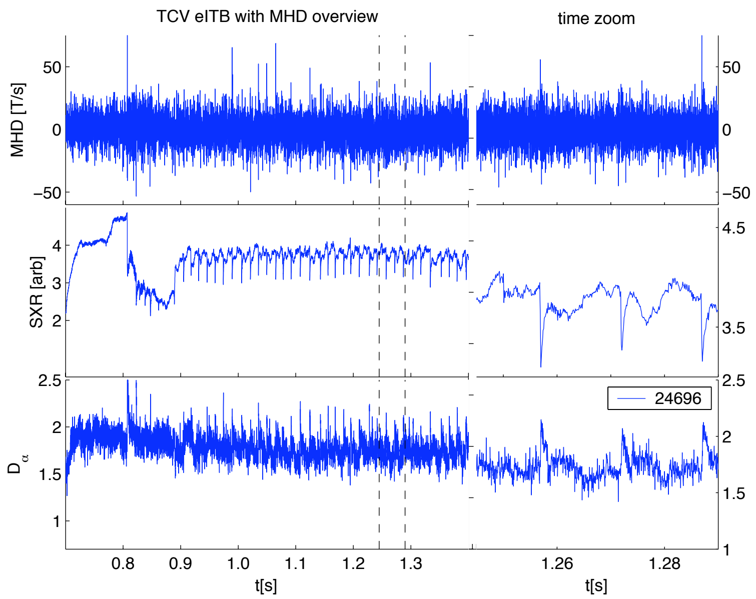

FIGURE 3. Shot 24696 overview. The top trace shows the Mirnov probe signal, indicating with the spikes the ideal activity at the crashes. The middle trace shows SXR core emission, with the periodic crashes after the eITB formation. The bottom trace shows Dα emission. On the right box, the zoom of the indicated time window is reported.

II.II Ideal MHD triggered global oscillations

As an example of ideal-mode triggered periodic global oscillations, discharge #24696 is reported here. In this experiment significant on-axis counter ECCD was added to off-axis ECH, in an inductive scenario. A significant Ohmic current was also present. In this eITB scenario [10] the ideal-like modes have the same global effect on the confinement (drop in the H-factor) and they resemble the so-called β-collapse observed in JT-60U [12] or the q=2 sawteeth previously observed in JET [11] . These crashes have a sawtooth-like behaviour of the core SXR is shown (proportional to electron

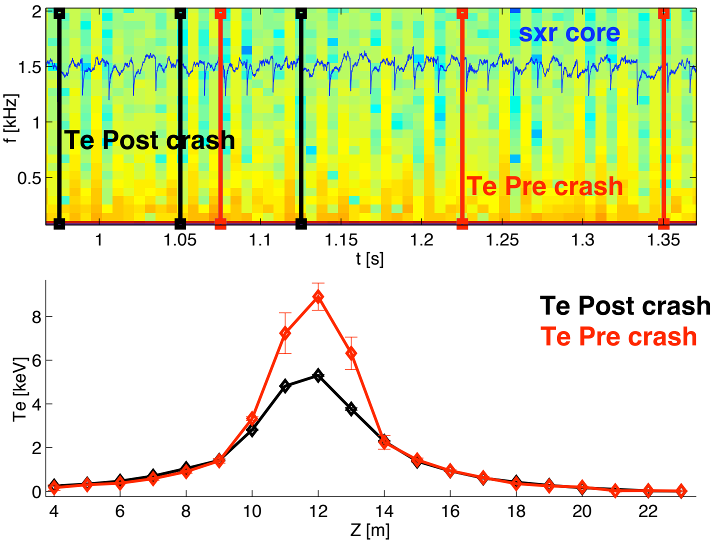

FIGURE 4. *Shot 24696 Thomson Scattering (TS) data. The top plot show sSXR spectrogram and SXR core raw trace (blue) evidencing the periodic crashes. The red lines shows TS profiles of pre-crash states, wheras the black one are taken during post-crashes states. The bottom plot reports the profiles, indicating the loss of electron temperature.*

temperature and density), with drops and subsequent rises (fig. 3 middle trace, zoomed on the right side of the figure) involving the region close to the q=2 surface.

The modes are ideal kink-like and they are dominated by high local pressure gradient at the barrier location. The destabilising factor is found to be the peaked pressure gradient in conjunction with a low magnetic shear, i.e. the infernal mode limit [8].

In terms of phenomenology, a large crash (on the Alfvèn time-scale) of type *m*/*n*=2/1 at t=0.81 s stops the initial fast growth of the eITB (fig. 3, middle-left plot). The crash triggers a *m*/*n*=2/1 resistive mode that is stabilised later. At this time the confinement improves again until the pressure gradient is strong enough to trigger a smaller ideal infernal mode, with a period τ~16 ms, which is responsible for the low H_{RLW} achieved for this discharge. The pressure peaking factor $p_{e0}/\langle p_e\rangle$ reaches 15 at t=0.81s, and this causes the relaxation of the pressure profile and a subsequent decrease in β. The following smaller crashes develop in a region with $p_{e0}/\langle p_e\rangle$~10 and $\beta\simeq0.75$ [10,14]. The evolution of averaged T_e profiles is given in fig. 4. Coherent averaging of T_e is achieved for pre-crash and post-crash states. The first (red lines, and bottom red profile) shows a much more peaked behaviour, which is relaxed by the infernal crashes due to the ideal infernal mode.

III. Global oscillations mitigation/stabilisation

In order to mitigate or stabilise the MHD instabilities that are responsible for the O-regime (resistive MHD induced global oscillation) one can act on the local magnetic shear near the foot of a barrier or on the pressure gradient. The first can be obtained with the addition of an inductively induced current to the steady-state current profile or with an EC current (different tokamaks may used other techniques). The combination of the two can be achieved by targeted deposition of the ECH power to modify the pressure profile. In TCV, these strategies have been successfully applied for the complete stabilisation of the global plasma oscillations [5,15].

The most successful attempt in this respect is described in [15] and reported briefly here in fig. 1. This is a fully-non inductive discharge with a large bootstrap fraction (40-45%). In this discharge the suppression of the oscillatory regime is achieved without causing the loss of eITB strength, and therefore by maintaining a constant H_{RLW} merit factor. In order to do so the total power of co-ECCD off-axis beams was continuously decreased from 1.5 MW at t=1.5s to 0.6 MW at t=2.2 s. To minimise the change in the total input power and therefore attempt to keep the strength of the barrier to its steady state value, thus to provide effective

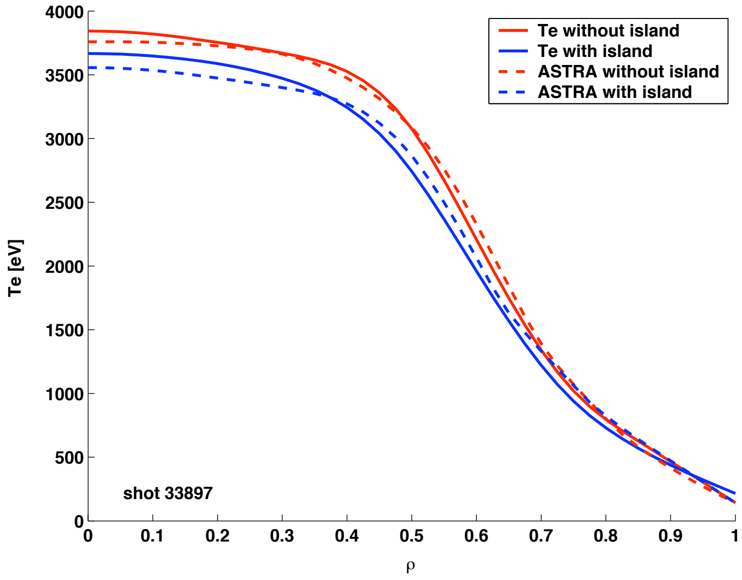

FIGURE 5. *Comparison of electron temperature experimental profiles (lines) and ASTRA modeling results (dots) for pre-MHD, top-performance state (red), and island saturation phase (blue)*

control without losing confinement properties, counter-ECCD on-axis has been added from 1 s to 2.2 s with a constant power of 0.25 MW.

On the one hand the reduction in co-ECCD should modify the shear in the already low shear region of q_{min}, on the other hand the q_{min} is moved away from the low rational value, which is confirmed by CQL3D [18] and ASTRA [16] simulations [3,15]. The experimental evidence is the suppression of the resistive MHD mode in a time comparable with the resistive time in TCV after the reduction of co-ECCD, i.e. a plasma further from marginal stability in the β-q_{min} space (fig. 2). The H_{RLW} increases from 3 to 3.5 after the suppression of the oscillatory regime, indicating that the transport barrier is well sustained. It should be noted that, unlike the resistive mode, the ideal n = 1 mode (with a dominant 3/1 component) can be unstable even if q_{min} is above 3, but as q_{min} rises further, the mode stabilises [8].

IV. ASTRA simulation of the MHD induced O-regime

We present preliminary simulations performed to compare the effects of magnetic islands on local transport and the change in profiles observed experimentally. Using the same discharge as in Fig. 1, we show in Fig. 5 the measured profiles at the top of the oscillations (solid red lines, ‘without island’) and at the bottom (solid blue line, ‘with island’). Using the power balance χ_e from experimental measurements at the top of the oscillation, keeping n_e fixed, we recover the T_e profile with ASTRA [16] simulation (dashed red line, ‘ASTRA without

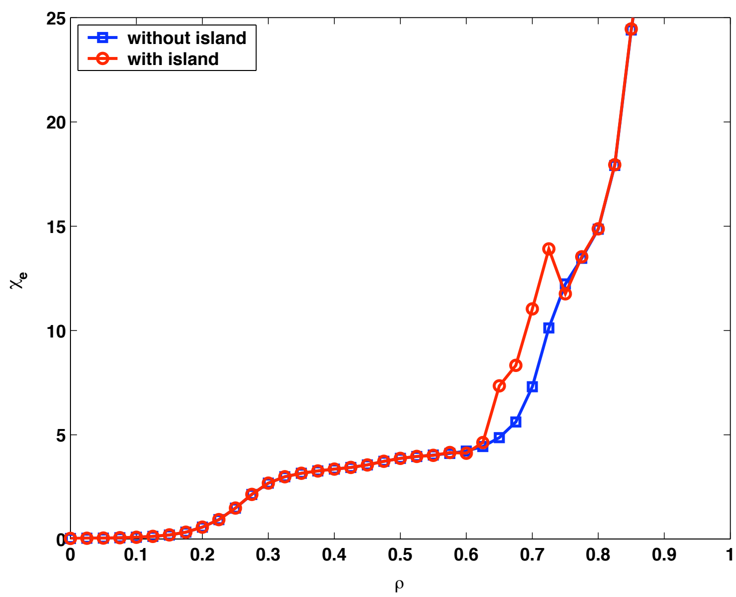

FIGURE 6. *Comparison of χ_e from ASTRA modeling for pre-MHD, top-performance state (red), and island saturation phase (blue)*

island').

The simplified model for the effect of an island is an increase of χ_e over the width of the island. From SXR tomography and magnetic data, a *m*/*n*=3/1 island of about 5 cm width located near the foot of the barrier is observed. Therefore, as a first approximation, we have just doubled the value of χ_e in this region as shown in Fig. 6. The perturbation is indeed located near the foot of the barrier, ϱ~0.7, since it is in the region with the large decrease of χ from ϱ=0.75 to ϱ=0.65.

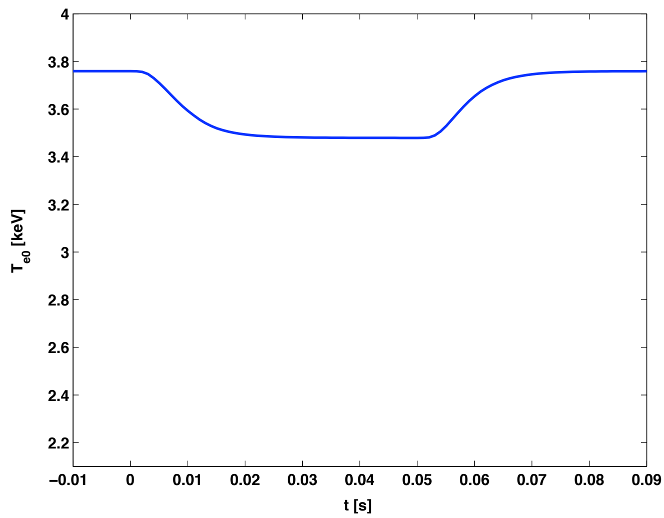

FIGURE 7. *ASTRA central electron temperature time evolution during the modeled appearance of the island. The new stationary state is reached in 20 ms, with a central drop of almost 300 eV.*

At this stage, we do not have a self-consistent model for the stability of the MHD mode, therefore we specify at some time the trigger of the island by changing the χ profile, and then remove the perturbation. In Fig. 7 we show the time evolution of the central T_e value and in Fig. 5 (dashed line, 'ASTRA with island') the stationary profile with the perturbed χ. One sees that this simple modification of $\chi_e(r)$, consistent with the mode location and width, encapsulates the measured modification of the T_e profile (solid lines in Fig. 5). The time constants are qualitatively correct as well, however one should also evolve the density since it is also affected by the mode and its time evolution characteristic is different. So these results are preliminary and are used here just to illustrate the coupling between the island and the plasma profiles.

V. Conclusion

Global oscillations in TCV are strongly related to the presence of MHD activity. In reversed shear scenarios, the development of global plasma oscillations can be ascribed to the proximity of the plasma to the infernal stability boundaries and the subsequent onset of a mode. In advanced scenarios these are related to the intrinsic current density (therefore shear) and pressure profiles whose destabilising effects act in the same region. Depending on the β_N-q_{min} values, the plasma can develop global oscillations due to the onset of ideal modes (β-collapse, q=2 sawteeth, minor disruptions) or resistive modes (O-regime,NTM). Thus, many events like $q \geq 2$ sawteeth, ß-collapses, minor disruptions and O-regimes can be assigned to the same physics origin: the proximity to the infernal mode stability limit.

If the plasma parameters are taken closer to the infernal stability boundaries, usually a major disruption terminates the plasma current. Therefore, understanding and controlling global oscillations is necessary for fusion reactors and ITER where advanced scenarios are candidate for steady state operation. These scenarios are only weakly controlled by external actuators, since most of the current profile is sustained by the bootstrap current.

In the recent years, TCV has shown that global plasma oscillations can be controlled by modifying the current density and/or pressure profiles, either with Ohmic current density perturbation or by modifying the ECH/ECCD power [5,15].

Simulations with transport codes are being carried out to analyse the consistency of the MHD-caused global plasma oscillations and the effect on transport. Initial results based on experimental profiles and modelling codes ASTRA and CQL3D seem to indicate that the MHD mode observed near the foot of the barrier can cause the observed drop in the plasma performances.

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