The role of MHD in the sustainment of electron internal transport barriers and H-mode in TCV

G Turri, O Sauter, L Porte, S Alberti, E Asp, T P Goodman, Y R Martin, V S Udintsev and C Zucca

Abstract. Advanced scenarios exhibit improved confinement properties, which make them attractive candidate for ITER. For these to be achieved, the sustainment of transport barriers and therefore high pressure gradients is inherent. Their stability properties both in the transient and steady state phases is a major issue [1], because of the relationship between high performances and proximity to a stability limit. Core MHD modes are one of the key issues in the development and sustainment of transport barriers, as they degrade the confinement properties and, in the worse case, disrupt the plasma. The understanding of the underlying physics can provide the means of finding regimes without modes. In TCV (Tokamak à Configuration Variable) H-mode and electron internal transport barriers (eITBs) have been obtained with different schemes, usually accompanied by various types of MHD phenomenon [2, 3, 4]. In this paper we focus on the low-shear Quasi-Stationary ELM-free H-mode (QSEFHM) scenarios [4], which displays infrequent sawteeth and/or NTMs. In addition to that, high-performance eITBs shots are discussed, during which a variety of resistive to ideal modes are observed and ascribable to the internal stability limit [3, 5]. Analysis of data from TCV highest performance discharges can clarify the potential threats of MHD modes in advanced scenarios. MHD core analysis of the QSEFHM [4], and of eITBs is presented, focusing on the existence of stability windows.

1. Introduction

In TCV (Tokamak à Configuration Variable) the ECH (Electron Cyclotron Heating) system allows to locally modify the electron density and temperature. The ECCD (Electron Cyclotron Current Drive) together with the neoclassical effects allow tailoring the current profile. Small and reverse magnetic shear plasma are routinely obtained, two instances of which are respectively the Quasi-Stationary ELM-Free H-Mode (QSEFHM, [4]) and high-performance eITBs (electron Internal Transport Barrier). These types of advanced scenarios, discussed in this paper, provide better confinement properties than conventional ones, mainly thanks to the reduced transport across flux surfaces, impeded by the arising of transport barriers.

The main characteristic of QSEFHM discharges is the transition to a quasi-stationary ELM-free H-mode phase which lasts for much longer than a confinement time, once the auxiliary heating is applied. This is not accompanied by density (and impurities) uncontrolled build-up often observed in ELM-free H-Modes, drawback of the conventional ELM-free scenarios. In
addition to that, the robustness of the QSEFHM makes it a potential candidate for future exploitation, subject to further understanding and investigation of its properties.

The formation and sustainment of eITB in TCV [6, 7] can also be accompanied by the development of MHD instabilities. The character of the observed instabilities varies from disruptive (ideal infernal mode) to resistive (tearing mode developing magnetic island, classical or neoclassical). In addition, the MHD instabilities can cause periodic, spontaneous, slow, global oscillations of the plasma (electron temperature, density, plasma current, SXR radiation, etc). These are reminiscent of the Oscillatory Regime (O-regime [8]), which was first observed in the Tore Supra tokamak. In TCV the MHD activity and the O-regime are linked, with the first being the cause for the second [9].

MHD modes are detrimental for the confinement as they enhance perpendicular transport, and could limit the access to higher confinement, as possibly in the case of discharges not developing the QSEFHM. Therefore, the study of the interplay between advanced scenarios and MHD activity is of crucial importance, as well as the implementation of ways to avoid instabilities or to limit their effects.

2. The Quasi-Stationary ELM-Free H-Mode - QSEFHM -

In TCV, H-mode is obtained with and without auxiliary electron cyclotron heating. The QSEFHM has been achieved in TCV by employing three gyrotrons at full power (1.4 MW, 118 GHz) with the vertical launcher at the third harmonic, X-polarization (X3). This regime appears to be fusion relevant because it displays good confinement properties, absence of ELMs without density and impurity uncontrolled build-up. Furthermore, the scenario is obtained with

![Figure 1. TCV Discharge #29892: overview of a discharge developing the quasi-stationary ELM-free H-mode. Transition A-B (top) occurs after the X3 heating is applied. At t=0.8 s, power is modulated (third plot) and soon after the plasma achieves the QSEFHM. The total and electron energy reach their maximum during the C-phase (second plot). The averaged density is almost constant (fourth plot) and the \( H_{\text{SSR}} \) reaches the maximum value \( \sim 3.2 \) (bottom plot). In phase D, a 3/2 NTM degrades slightly the performance.]

no momentum input, and in target plasmas (\( \beta_N \sim 2 \) and \( q_{95} = 2.5 \)) that are ITER relevant. Finally, TCV is in the unique position to be able to achieve H-mode by heating solely the electrons, leaving the ions to be heated by ion-electron collisions, a scenario that mimics that
of a burning plasma [4]. The QSEFHM (figure 1) is characterized by a H-mode without ELMs (top plot, phase C and D), high energy content (second plot), high constant plasma current (third plot, corresponding to $q_{95} \sim 2.5$), approximately constant electron line-averaged density $n_{el}$ (fourth plot). The Ohmic H-mode phase (A) begins at $t \approx 0.4\, \text{s}$ and is characterized by small and frequent ELMs. These ELMs do not display any particular MHD precursor. The sawtooth crashes and the ELMs are not coupled. The X3 heating starts at $t = 0.6\, \text{s}$, which causes the transition between phases A and B in figure 1. The ELMs become larger, and the frequency drops from 230 Hz to 60 Hz. At this time the increase in plasma energy can be observed from the energy trace (second plot, red trace). During the B phase, the three gyrotrons are used at full power (third plot, red trace). At $t = 0.8\, \text{s}$, one of the three gyrotrons is power modulated ($f = 240\, \text{Hz}$), slightly before the QSEFHM begins (Do emission, top plot). At $t = 0.83\, \text{s}$, the last ELM marks the beginning of phase-C, the quasi-stationary phase (QSEFHM). This phase does not show variation in the plasma current and averaged electron density. The plasma total energy (black trace, second plot) and electron energy (blue trace) reach their maximum value, which is kept stationary during the C-phase. The $H_{90P}$ scaling gives an average value 2.7 during this phase C underlying the improved confinement. At $t \approx 1.1\, \text{s}$, a big ELM causes a large drop in the SXR emission and energy. Conversely, the ELM does not cause any change in the averaged density. This single ELM marks the transition between the first (C) and the second QSEFHM phase (D), with the latter displaying a lower energy content.

The various levels of confinement properties can be better appreciated by following the evolution of the electron temperature and density profiles throughout the four phases of the QSEFHM discharge (figure 2). The top plot shows the spectrogram of the central soft X-ray signal (digitized at 200kHz), with a mode starting at 1.1s whose onset is linked to the large ELM separating phase C and D (Do emission, blue). Four time windows are chosen during the different phases, characterized by colored vertical lines. The violet profiles (electron density, bottom left; electron temperature, bottom right) represent the average Thomson Scattering (TS) profiles

![Figure 2. TCV Discharge #29892: the variation of the electron temperature and density profiles can be used to follow the different confinement properties of the four phases. The pedestal is almost constant during the H-mode, and the best confinement is achieved during the QSEFHM. The ELMy (X3) H-mode (green) and the second QSEFHM with an NTM (red) are similar in terms of confinement.](image-url)
during the Ohmic ELMy H-mode. The density is as high as for the QSEFHM (no changes in the gas puffing are implemented throughout these phases), while the electron temperature is less than one third in the core. After the X3 heating is applied, the density slightly drops (-17%, larger ELMs) but the electron temperature strongly increases (green). The blue vertical lines delimit the QSEFHM: during this phase the confinement properties are the highest for both the electron temperature and density. The large ELM at \( t \sim 1.1 \text{s} \) triggers a NTM mode at frequency \( f \sim 15\text{kHz} \), which reduces the energy (figure 2, spectrogram plot, and also visible in figure 1, second plot) with the temperature and the density being lower when compared to C-phase. Their product is almost constant, suggesting that the effect on confinement of this NTM in the absence of ELMs is similar to the X3 heated, ELMy H-mode.

In the following subsection, a characterization of the MHD activity during the different phases is reported.

2.1. MHD characterization of the QSEFHM

The different phases (B to D, figure 1) show varying MHD activity, which plays an important role in defining \( \beta \) and \( W \) (the total thermal energy).

- **B**: In the X3 heated phase the ELMs are larger and their frequency lower. The core is stabilized against the sawtooth instability. The Soft X-Ray (SXR) radiation profiles in this case do not show any inversion radius, instead a global collapse of the radiation profile up to the center is observed at every ELM, with subsequent loss of the pedestal. Sometimes in between ELMs, a coherent \( m/n=2/1 \) oscillation is observed. This mode at \( f \sim 3\text{kHz} \) lasts for a few milliseconds after the crash, and it is then stabilized during the inter-ELM time, thus not having a significant impact on the confinement.

- **C**: During this phase, there is intermittent \( m/n=2/1 \) activity with \( f \sim 5\text{kHz} \), which appears in bursts. The frequency is almost double than that of the 2/1 observed in phase-B, and the size smaller. Small SXR crashes are likely to be related to the \( m/n=2/1 \) mode, rather than being sawtooth crashes. This is because they appear to be linked to the mode, and the SXR profiles does not suggest sawteeth activity.

- **D**: The D-phase is characterized by the single ELM event which triggers an NTM mode with \( f \sim 15\text{kHz} \), and main periodicity \( m/n=3/2 \). This mode has the same periodicity of a magnetic island developing in a similar discharge that will be discussed in 2.2. The NTM in this discharge has a much higher frequency and smaller effect on confinement. Indeed, the island full width is approximately \( w \sim 5\text{cm} \). This corresponds to an expected drop in energy of \( \Delta W \sim 25\% \), consistent with the drop in electron energy from the reconstruction (~20%, figure 2). The resulting confinement level, from the electron energy calculations and the pressure profile from TS is comparable to that of the B-phase, i.e. that of an ELMy, X3-heated H-mode. The fact that the D-phase follows a major crash and the QSEFHM is recovered despite of the presence of an NTM mode is a sign of robustness of the scenario. The QSEFHM is therefore a viable scenario for ITER and burning plasmas. In order for it to be exploited the uncertainties regarding its attainment (in the following section a similar shot not developing the quasi-stationary regime is discussed), and the potentially lethal singular ELM events require further studies.

2.2. Comparison between ELMy X3 H-mode and QSEFHM

Discharge #29894 (figure 3) was obtained with the same settings as discharge #29892 (QSEFHM), except for the power modulation. The pre-X3 phase for the two discharges are the same, with similar plasma current, electron density, plasma shape (\( l_1, k, \delta \)). As soon as the X3 power is switched on, a large \( m/n=3/2 \) mode appears at low frequency (\( f \sim 6\text{kHz} \)). This is at a time before the power modulation for #29892, hence the absence of it cannot be the cause
for the mode onset. In discharge #29894, the mode rotation speeds up during the ELM-free phase lasting for approximately a confinement time ($t \sim 50\text{ms}$), and then it slows down just before the first ELM. At the ELM event the frequency spectrum shows a steep deceleration of the mode, which is repeated for all the other ELMs (possibly suggesting a locking of the edge mode with the vessel, due to finite resistivity of the wall), all of which separated in time by approximately a confinement time. The $m/n = 3/2$ mode is non-linearly coupled with a $m/n = 2/1$ at $f \simeq 3kHz$. The mode closer to the core, i.e. the one at the $q = 1.5$ resonant surface, is the dominant one. From a bi-coherence analysis (figure 3) the coupling (if any) of the two modes can be verified. The analysis consider the frequency relation between two coherent modes and the phase information within the Fourier transformation in the frequency space [10]. In figure 3 the correlation level between the two modes is approximately 0.7 at the frequency equal to the combinations of the two modes fundamental frequencies, $f_1 \pm f_2$. This means that the two modes are phase-locked. The confirmation of the existence of two separate, phase-locked modes, is also obtained through magnetic island modeling [11], where current filaments are simulated at the flux surfaces reconstructed with the LIUQE [12] code. The perturbed magnetic field is then extrapolated to the poloidal magnetic coils placed around the vessel at different poloidal locations. The result gives the degree of confidence on the mode periodicity, which is mainly $m/n=3/2$ with non negligible $2/1$ component. Furthermore, at a later time the lower frequency mode ($m/n=2/1$) is stabilized for 50ms after an ELM, whereas the dominant 3/2 remains. Finally, the bi-coherence plot during this time interval does not show any similarities with that obtained during the times when the two modes are coexisting.

Figure 4 shows the dual multiwire proportional x-ray (DMPX) detector array reconstruction of the modes [13], with the iso-surface of perturbed SXR emission for the $m/n=3/2$ mode. The black lines represent the maximum extent of the $m/n=2/1$ mode, for which the interpolation returns larger error bars. Hence, these are the extremes $\rho_s$ occupied by the external island, not its real contours. This reconstruction is useful to add resonance points on the q-reconstruction by LIUQE (figure 4). The diamond represent the best fit for the DMPX signals, and the horizontal line is an error-bar $\pm 7\%$ of the central location, with this value chosen according to profile inversion simulation.
Figure 4. TCV Discharge #29894: the m/n = 3/2 and 2/1 locked modes are reconstructed (left) with the high-spatial resolution SXR diagnostic. This allows to add constraints for the q-profile reconstruction (right).

Figure 5. TCV Discharge #29894: comparison of the electron pressure profile between X3 heated ELMy H-mode phase for 29892 and 29894. It is evident the drop in confinement (red) due to the presence of the coupled modes.

This is useful to provide further constraints when running plasma transport simulations. The effect of the mode can be observed through the detailed comparison of the averaged TS profiles between the X3 heated phases of the two discharges (figure 5). In the Ohmic phase the two pressure profiles overlap. As soon as the X3 heating is started, discharge 29894 (second spectrogram from the top, figure 5) shows the coupled modes, together with ELMs. In discharge 29892, instead, only the ELMs and intermittent m/n = 2/1 activity are observed. It is interesting to point out that discharge 29892 did not access QSEFHM during the full power phase, without an MHD mode, but only when the modulation had started. Because of the lack of available plasmas with QSEFHM and the apparent contradiction of this, further experiment will be run in the next campaign with and without modulation. It should be noted however that QSEFHM phases have been obtained without power modulation.

Figure 5 shows a comparison of the X3 heated ELMy H-mode phase of discharge 29892 (no modes) and 29894 (with 3/2 and 2/1 modes coupled). The effect of the 3/2 island (\( w \approx 7 \text{ cm} \)), which corresponds to a loss in confinement of approximately 33% in agreement with the pressure drop between 29892 and 29894 (figure 5).

The development of the QSEFHM might require sufficient pressure gradients; it is possible that the 3/2 mode causing a significant drop in the confinement properties is preventing the appearance of the ELM-free quasi-stationary state. This statement requires further
investigation, and further experiments are planned for the next TCV campaign.

3. **Electron Internal Transport Barriers (eITBs) and the effect of MHD**

Scenarios involving MHD instabilities during the flat-top of eITBs are the interest of the second part of this paper. The character of the observed instabilities varies from disruptive (ideal infernal mode) to resistive (tearing mode developing magnetic island with or without a neoclassical contribution). Figure 6 shows two eITB experiments displaying ideal-like events: TCV discharge #21653 and #24696. The first one (blue) reaches a very high confinement factor ($H_{RLW}$ up to 6) thanks to a significant reverse shear $q$-profile. This causes a fast approach to the ideal stability limit because of the improved confinement. At $t \simeq 1.28s$ a major disruption ideal event (ideal infernal mode [5]) terminates the discharge.

![Figure 6](image.png)

**Figure 6.** MHD overview for discharges #24696 (red) and #21653 (blue). From top to bottom: magnetic Mirnov raw signal, SXR emission from the core of the plasma, $D_\alpha$ emission. On the right-hand side, zooms of the time window delimited by the vertical dashed lines on the left.

![Figure 7](image.png)

**Figure 7.** Thomson Scattering pressure profile from raw data (blue), with basic fit (red) and $q$-profile from CQL3D [14] for discharge TCV#21655. $q$-min~2.7 at $\rho=0.5$ [5].

This is shown in details on the right side of figure 6, where the time zoom of the traces
between the two vertical dashed lines is reported. For this discharge (figure 6) the non inductive current \(j_{CD}\) generated off-axis, in addition to the bootstrap current density \(j_{BS}\), led to a hollow current density profile. The effect of the gyrotron on-axis added at \(t = 1.1s\) is evident in the middle blue trace of figure 6, with the steep increase in SXR emission [7]. The current profile for a similar discharge #21655 but with slightly less counter-CD in the center has been reconstructed thanks to the Fokker-Planck code CQL3D (figure 7), resulting in a \(q_{min} \approx 2.7\) at the radial location \(\rho_\psi \approx 0.5\), where the barrier is formed [5, 15]. Magnetic signals analysis reveals the presence of MHD modes with periodicity \(m/n = 3/1\) and \(2/1\) during the disruption of #21653, with a growth time \(\tau_{MHD} \approx 20\mu s\), which is typical for ideal instabilities in TCV. For discharge #21655, analysis with KINX code reveals an unstable ideal infernal \(3/1\) mode with a significant \(2/1\) component, for \(\beta_N\) larger than 1. The \(\beta_N\) experimental value is close to unity, confirming that discharge #21655 is close to ideal stability threshold, with \(q_{min}\) near 3 (figure 8). The instability is caused by a high pressure gradient at \(\rho_\psi \approx 0.5\), where the eITB is formed in a low-shear region. This is the characteristic of infernal modes. Infernal mode appears in regions of low-shear [16]. In this region the development of low-\(n\) pressure-driven modes is possible, which was first described in [17] for reversed shear profiles. TCV plasmas are generally stable against the \(1/1\) mode, as \(q_{min}\) is generally above the values for which the internal kink is unstable. Infernal and external modes with \(m=2,3,4\) can develop when \(q_{min}\) is close to those integer values [5].

![Figure 8](image)

**Figure 8.** The \(n=1\) mode stability boundary plotted in \(q_{min}\) space. Green and red squares correspond to ideally stable and unstable configurations respectively. \(\beta_N^{exp}\) is plotted for TCV discharge #21655

From the evolution of the Thomson Scattering profiles, these modes are clearly detrimental for the attainment of a steady state internal transport barrier. This is a major goal for a fusion reactor, as the confinement for this regime is highly enhanced compared to that of non-advanced scenarios. A way to avoid infernal modes is to tailor the q-profile through fine adjustments of the injected power in order to move the \(q_{min}\) away from the minimum values of 2 and 3, or to slightly reduce the local pressure gradient. For \(q_{min} > 4\), the infernal mode becomes an external kink mode, which is less sensitive to the values of \(q_{min}\) [5].

The red trace in fig. 6, TCV discharge #24696, represents a different scenario involving ideal crashes with a slightly different character [18]. These ideal-like modes have the same detrimental effect on the confinement and they resemble the \(\beta\)-collapse observed in JT-60U [19]. These crashes have a *sawtooth-like* behavior of the electron temperature, with drops and subsequent rises (fig. 6, middle red trace, zoomed on the right side of the figure). It is found
that each crash involves the region close to the $q = 2$ surface, i.e. the same region involved in the presented infernal modes. This type of mode has also been previously observed in JET [20]. During this discharge (figure 6, red trace) on-axis counter ECCD was preceded by off-axis ECH, which resulted in a broader electron temperature profile. A significant Ohmic current was also present [18]. Thus, current and pressure profiles are different from the experiments described above, and ideal periodic modes develop. The mode is ideal kink-like and it is dominated by high local pressure gradient at the barrier location (low shear) and global $\beta$ limit. Therefore the same characteristics as the infernal mode limit discussed above for #21653. The pressure profile obtained from TS measurements together with the modelling of the $q$-profile through the Mirnov coils data and DMPX inversion analysis shows that the strong pressure gradient is localized in the region of the minimum of the safety factor, i.e. the region of low shear. This is destabilizing the infernal mode, according to the modeling reported in [16] and figure 8. A fast, large crash of type 2/1 at $t = 0.81s$ stops the initial fast growth of the eITB. The crash trigger a 2/1 resistive mode that is stabilized later.

![Figure 9. MHD overview for discharges #32029 (red) and #32023 (blue). From the top to the bottom: magnetic Mirnov raw signal, SXR emission from the core of the plasma, $D_\alpha$ emission. On the right side, zooms of the time window delimited by the vertical dashed lines.](image)

At this time the confinement improves again until the pressure gradient is strong enough to trigger another infernal mode, with a period $\tau \approx 16ms$, which is responsible for the absence of higher $H_{RLW}$ for this discharge. The pressure peaking factor ($p_{e0} / <p_e>$) reaches a very high value ($\approx 15$) at $t = 0.81s$, and this causes the relaxation of the pressure profile and a subsequent decrease in $\beta$. The following smaller crashes develop in a region with $p_{e0} / <p_e> \approx 10$ and $\beta_N \approx 0.75$.

Regarding experiments displaying a resistive character, figure 9 shows two discharges of global plasma oscillations. The blue traces refer to discharge #32023, on-axis counter-ECCD with Ohmic contribution. The oscillations are fast and dominated by an initial ideal phase which triggers the longer lasting ($\approx 2 - 5ms$) resistive phase, where the topology of the plasma is changed by the appearance of a small magnetic island. This discharge is characterized by regular small infernal mode crashes with frequency $f \approx 20Hz$. This type of regime, with the continuous bursts of ideal activity which are followed by a longer lasting resistive mode, causes electron temperature oscillations that are triangular-like due to the ideal character. Figure 10 shows a selection of plasma parameters evolving during four events. The spectrogram of magnetic signal (top trace) allows to appreciate the dual character of these oscillations. Every event is
Figure 10. Overview of regular mixed ideal-type and resistive instabilities, discharge TCV #32023. From the top: magnetic spectrogram, indicating the fast ideal phase followed by a resistive mode. Plasma current (blue) which reaches the top at the onset of the infernal modes. SXR radiation from the core (red), showing the crashes at the ideal event. Plasma density (green). D-α light (black). $V_{\text{loop}}$ (magenta) showing the continuous changes in the magnetic configuration.

characterized by an ideal crash, which is responsible for the almost vertical signature indicating a large band of frequencies, from $15kHz$ to $5kHz$. The ideal phase can be observed also in the SXR trace (red, third from top) and Dα light (black, 5th from top). The drop in the SXR at the occurrence of the ideal mode indicates the fast collapse of the barrier, which is generally accompanied by the emission of light. These events happen at the top of the confinement phase (highest SXR core signal), where the plasma is unstable to the infernal mode. The secondary mode is different in character and separated by the first. It is resistive and lasts for approximately $\Delta t \simeq 20ms$. The magnetic island has a $2/1$ periodicity, which is also the main component of the ideal event. The plasma current (blue, second trace) shows oscillations ($\Delta I \simeq 10kA$) with the top of the plasma current synchronous with the ideal mode. The change in the current is smoother than that of SXR radiation, as these crashes are small and the current diffusion time is much longer than the MHD time. The average density oscillates almost in phase with the SXR radiation, but with a smoother behavior. This is an indication of the different electron temperature and density dynamics. The $I_p$ trace in particular shows that even cycles triggered by ideal modes can lead to oscillations similar to the so called O-regime [8]. The $V_{\text{loop}}$ follow the general behavior of the other traces, indicating the continuous evolution of the magnetic configuration during this oscillatory regime. The drop in SXR emission during the small infernal crashes (proportional to the loss of confinement) is very limited (10% of the signal in the core). The plasma appears to shrink during the ideal mode, which probably leads to a removal of the barrier and the subsequent loss of confinement.

Discharge #32029, fully non inductive, is unique because it shows both type of modes in a distinctive way (figure 9, 0.8s $\leq t \leq 1s$ for the infernal mode unstable plasma, 1.2s $\leq t \leq 1.5s$ for the resistive mode). At the time when the barrier is formed ($t \leq 0.8s$) the electron temperature suddenly increases (fig. 9). We can infer the beginning of an extremely large global oscillation, with a full cycle completed before an ideal instability provokes the abrupt collapse of the temperature. The zoom on the right part of figure 9 shows the first big crash at $t \simeq 0.908s$, which alone does not stop the oscillations. The radiation profiles before and after the crash show the character of a sawtooth-like instability, with an inversion radius that is located in the proximity...
of \( q = 2 \). The drop in SXR radiation, proportional to the loss of confinement, is approximately 60% of the emission in the core. The gradients at the barrier are lost and expulsion of particles and heat is observed. Based on the pressure profile and the phenomenology of the mode, the crash appears to be the result of a major infernal mode, just not large enough to disrupt the plasma as in #21653. It could be called a minor disruption or a \( \beta \)-collapse. In effect, it is a crash triggered by an ideal \( n = 1 \) infernal mode. The applied heating, and the change in pressure profile, allows the quick recreation of the barrier. The second time the SXR trace reaches the top (\( t \approx 0.95s \)), a smaller infernal mode is observed. This reduces the confinement and begins a second phase with frequent, small infernal modes \( (1s \leq t \leq 1.2s) \), which has a detrimental effect on the confinement and prevent the development of an eITB. These tinier collapses \( (t \geq 0.95s, \text{ red trace}) \) are very frequent \( (\Delta t \approx 5ms) \) and accompanied by MHD oscillations \( (f \approx 15kH z) \). Later on the ideal modes are stabilized. At \( t = 1.22s \) the eITB begins to reform (red middle trace, figure 9), which is accompanied by the development of a resistive tearing mode \([9]\). This mode involves the periodical growth and shrink of a magnetic island located near the foot of the barrier. At the top of the oscillations the island has the minimum width and begins to increase in size, very rapidly. This reduces the confinement factor until the bottom of the oscillation; at this time the island is essentially stabilized, the confinement improves, and the cycle starts over.

The main periodicity of the mode, obtained by concurrent analysis with Magnetic coils, Soft X-ray tomography (SXR), singular value decomposition (SVD) and Fourier analysis reveals a 2/1 character \([9]\).

4. Conclusions

The role of MHD stability and control is of crucial importance for the development of steady-state advanced scenarios in tokamak plasmas. Ohmic and ECH heated H-modes are routinely obtained on TCV, displaying type-I ELMs and other types of MHD instabilities. If X3 power is injected from the top, and the conditions in terms of plasma parameters and shape are met (together with the absence of large MHD modes) the plasma can access a quasi-stationary ELM-free H-mode (QSEFHM), with better confinement properties and absence of ELMs. The reasons for the attainment (or not) of this regime are still partly unknown, and further experiments are planned. The positive aspects are the absence of ELMs, the improved confinement, the robustness of the regime and the absence of uncontrolled density build-up. On the other hand, the regime cannot be easily reproduced and sometimes large ELMs are seen to interrupt the quasi-stationary phase, inducing a threat for the maximum thermal load and the possibility of triggering tearing modes, as in #29892. MHD stability plays a fundamental role, since discharges without large magnetic islands have confinement properties up to 30% higher than discharges that develop MHD modes. In addition, no discharge has been found (up to this time) that develops the QSEFHM when the X3 heating triggers a mode on the \( q=1.5-2 \) rational surfaces before entering the quasi-stationary phase. Understanding the interplay of core MHD with the scenario achievement (if any), and the stability properties of X3 heated ELMs is a key factor for the reproducibility and safe operation of the QSEFHM. The sizes of the tearing modes discussed in this paper are consistent with the observed loss of confinement, stressing the importance of MHD control for plasma performances.

Regarding electron internal transport barriers, values of \( H_{RLW} \) higher than 4 have been obtained during eITBs discharges in TCV, with and without the development of MHD instabilities. MHD modes can be of ideal type or resistive (tearing modes, NTMs), and all the intermediate states are possible. The origin of these modes is the unfavorable conjunction of large pressure gradient in a low shear region, i.e. they represent the infernal stability limit \([5, 17, 16]\). Since eITBs are essentially obtained in reverse shear plasmas and occur near \( q_{\min} \), large gradients in small shear regions are inherent of these scenarios. Therefore it is likely that the various regimes described in the literature, \( \beta \)-collapse, \( q=2 \) sawteeth, O-regime, minor and
major disruptions in reverse shear are all related to the nearby stability limit of infernal modes, as observed in TCV. This is why they are sensitive to $q_{\text{min}}$, $p_0/ \langle p \rangle$, $p'$ and magnetic shear [5].

The effect of all these modes is detrimental for the barrier. Avoidance of the ideal modes is necessary because of their fast growth and thus the impossibility of controlling them once developed. This can be achieved by changing the current density and pressure profiles to avoid the proximity to rational integers of the safety factor and/or to reduce the local pressure gradient. The effects of the resistive modes are less abrupt, as they slowly change the topology and act on the resistive time. Nevertheless, the integral effect on the plasma confinement properties can be as much damaging as that of the ideal mode. Favorable for these modes is the fact that they can be detected by the plasma control system, which can react in order to stabilize them, by changing the profiles for example with local ECCD. Experiments with Ohmic contribution and current injection to prove this principle have been successfully achieved [2, 9].

References
[1] Strait E J 1994 Phys. Plasma 1 1415
[2] Udintsev V S et al. 2007 Fusion Sci. Technol. 52 161
[3] Turri G et al. 2007 IAEA Technical Meeting Steady State Operation, Daejeon - Korea
[4] Porte L et al. 2007 Nucl. Fusion 47 952
[5] Martynov A 2005 PhD thesis, Ecole Polytechnique Fédérale de Lausanne 3218
[6] Sauter O et al. 2005 Phys. Rev. Lett. 94
[7] Goodman T P et al. 2005 Plasma Phys. Control. Fusion 47 B107
[8] Giruzzi G et al. 2003 Phys. Rev. Lett. 91
[9] Turri G et al. 2008 Plasma Phys. Control. Fusion 50 065010
[10] Raju D et al. 2003 Plasma Phys. Control. Fusion 45 369
[11] Reimerdes H 2001 PhD thesis, Ecole Polytechnique Fédérale de Lausanne 2399
[12] Hofmann F and Tonetti G 1988 Nucl. Fusion 28 1871
[13] Rossel J 2005 LRP-report EPFL - CRPP
[14] Parail V V 2002 Plasma Phys. Control. Fusion 44 A63
[15] Henderson M A et al. 2003 Phys. Plasmas 10 1796
[16] Manickam J et al. 1987 Nucl. Fusion 27 1461
[17] Ozeki T et al. 1993 Nucl. Fusion 33 1025
[18] Zhuang G et al. 2004 31th EPS Conference on Plasma Phys., London, 2004 28G P-2.143
[19] Pomphrey J et al. 1996 Plasma Phys. Control. Fusion 38 1791
[20] Hender T C et al. 2002 Plasma Phys. Control. Fusion 44 1143