MHD detrimental effect on the confinement during flat-top eITB plasmas on TCV

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Abstract. Fully non-inductive scenarios with electron Internal Transport Barriers (eITBs) are routinely obtained on the Tokamak *à* Configuration Variable (TCV) by means of Electron Cyclotron Current Drive (ECCD) and Electron Cyclotron Heating (ECH) [1]. The flexibility of the gyrotrons available on TCV allows the study of different regimes in terms of barrier strength, barrier locations and presence or absence of Magneto Hydro Dynamic (MHD) instabilities. Various combinations of on/off-axis, co/counter-current injection and electron cyclotron heating has been used to obtain eITBs in reversed-shear discharges with confinement enhancement factors (H_{RLW}) above 4 [2]. Under certain circumstances, the plasma exhibits global m/n=0/0 oscillations coexisting with low rational q-surfaces MHD activity [3]. The ITB strength (observed through the variation of electron temperature and density profiles given by Thomson scattering) oscillates periodically between the minimum in correspondence with the fast growth of the instability, and the maximum achieved when the mode is stabilized [4]. Small differences in heating/current drive scenarios result in changes regarding the MHD behavior; the whole plasma is affected displaying crash-type sudden changes of the confinement when the MHD character is ideal-like, and slow modifications of the confinement (and ITB characteristics) in discharges with evidence of resistive MHD (reminiscent of the oscillatory regime observed in TCV and Tore Supra [5]). In this paper we describe the features of the different scenarios, focusing on the interplay of the eITBs with the MHD modes. It is also shown that these modes are consistent with so-called infernal modes destabilized by the large pressure gradient in a low magnetic shear region [6, 7].

1. Introduction

The formation of electron internal transport barriers in TCV is generally obtained with the current profile evolving gradually from a centrally peaked to a non-monotonic current profile. According to ASTRA [8] modeling, this process is consistent with the appearance of a local minimum in the q-profile [1, 2]. The formation occurs rapidly ($t < \tau_{eE}$) and locally [9]. Internal transport barriers can be created without

Ohmic contribution, i.e. by means of non-inductively driven currents and the resulting neoclassical bootstrap current contribution. The eITBs are then sustained for many current redistribution times, with or without the development of MHD activity depending on the plasma parameters, formation scheme and safety factor profile. TCV eITBs are generally limited in time by the gyrotrons pulse length [1]. Of particular interest for this paper are those scenarios involving MHD instabilities during the flat-top of eITB (figure 1 and figure 2). The character of the observed instabilities varies from disruptive (infernal mode, TCV discharge 21653, figure 1) to resistive (tearing mode developing magnetic island with or without a neoclassical contribution, figure 2, discharge 32029). The MHD instabilities sometimes determine periodic spontaneous slow global oscillation of the plasma (electron temperature, density, plasma current, emitted radiation, etc). This *regime*, also known as Oscillatory Regime (O-regime [5]), was observed first in the Tore Supra tokamak where a relation between the slow oscillations and MHD instabilities has not been found. In TCV, instead, the two are univocally linked and no O-regime has been observed in the absence of MHD phenomenon.

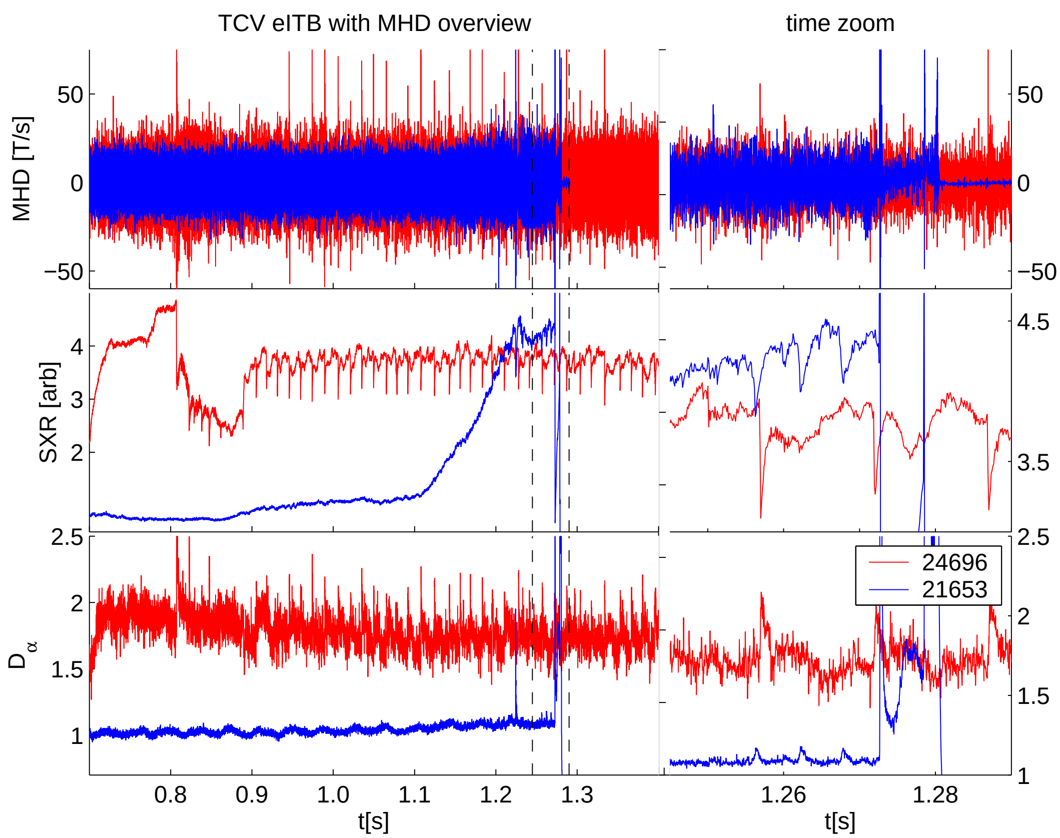

Figure 1: *MHD overview for discharges #24696 (red) and #21653 (blue). From the top to the bottom: magnetic Mirnov raw signal, SXR emission from the core of the plasma, Dα emission. On the right side, zooms of the time window delimited by the vertical dashed lines.*

Depending on the auxiliary heating applied, the current drive and the presence/absence of Ohmic current, different evolutions in terms of the oscillations size, frequency, and the location of the triggering MHD are observed. The frequency of the slow oscillations is in the range f=5-15kHz, and the electron temperature variation, from top to bottom of the oscillation, is up to 50% of the maximum value.

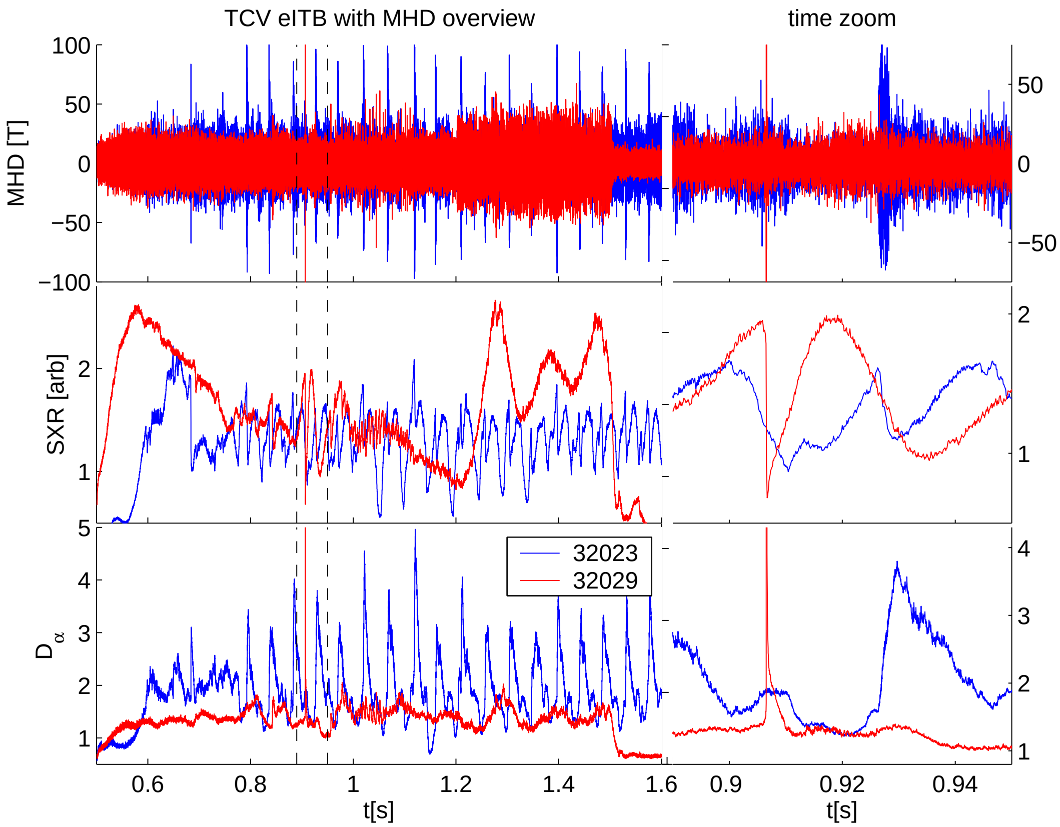

Figure 2: *MHD overview for discharges #32029 (red) and #32023 (blue). From the top to the bottom: magnetic Mirnov raw signal, SXR emission from the core of the plasma, Dα emission. On the right side, zooms of the time window delimited by the vertical dashed lines.*

Figure 1 shows two eITBs experiments all displaying ideal-like events: TCV discharge #21653 and #24696. The first one reaches a very high confinement factor (H_{RLW} up to 6) thanks to the toroidal angle of injection, and the subsequent strong reverse shear. This determines a fast approach to the ideal stability limit because of the resulting current and pressure profiles. At t≃1.22s a major disruption ideal event (ideal **infernal** mode [7]) terminates the discharge. This is shown in details on the right side of figure 1, where the time zoom of the traces between the two vertical dashed lines is reported.

The red trace, TCV discharge #24696, represents a different scenario involving ideal crashes with a slightly different character, called Periodical Relaxation Oscillations (PRO) in reference [10] that first described them on TCV; these ideal-like modes have the same global effect on the confinement (i.e. a drop in the H-factor) and they resemble the β-collapse observed in JT-60U. These crashes have a *sawtooth-like* behavior of the electron temperature, with drops and subsequent rises (fig. 1, middle red trace, zoomed on the right side of the figure). It is found that the 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 [11]. Regarding experiments displaying

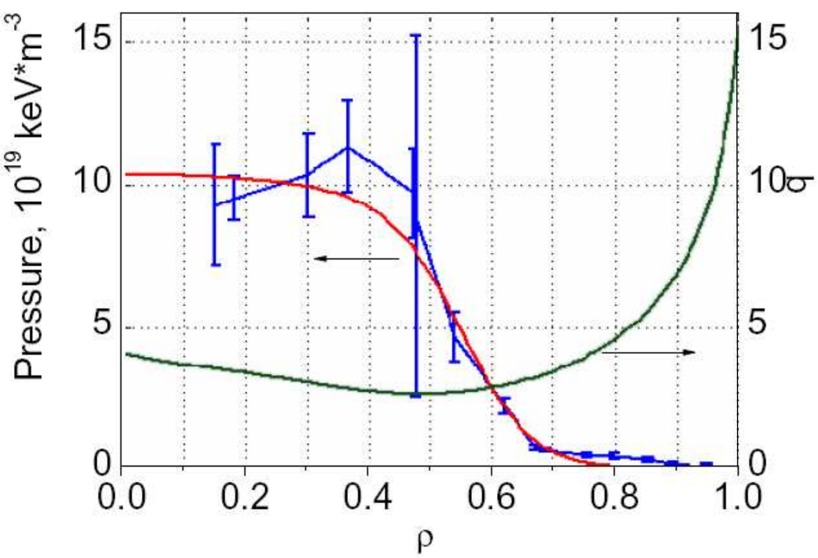

Figure 3: *Thomson Scattering pressure profile from raw data (blue), with basic fit (red) and q-profile from CQL3D [12] for discharge TCV#21655. q-min∼2.7 at* ρ*=0.5 [7].*

a resistive character, figure 2 shows two discharges of global plasma oscillations. The blue traces refers to discharge #32023, on-axis counter-ECCD with Ohmic contribution. The oscillatory character appears evident throughout the existence of the eITB. The oscillations are fast and, when looked at more closely, dominated by an initial ideal phase which triggers the longer lasting ($\simeq$2-5ms) resistive phase, where the topology of the plasma is changed by the appearance of a small magnetic island. The second discharge shown in figure 2 displays the emission for a fully non inductive discharge, TCV #32029 (red trace). The first phase (t$\leq$1.2s) shows slow, huge oscillations which are terminated by ideal MHD (infernal mode). The zoom in the right part of figure 2 shows the first big crash at t$\simeq$0.92s, which alone does not stop the oscillations. At this time the barrier is lost, but the applied heating allows the quick recreation of the barrier, and at the second time the SXR trace reaches the top, a smaller infernal mode is observed. This reduces the confinement and begins a second phase with frequent, small infernal modes (1s$\leq$t$\leq$1.2s). This has a detrimental effect on the confinement and prevent the development of an eITB. This can be noticed through the SXR emission in the core which slowly decreases until t=1.2s. At a later stage, t$\geq$1.25s, the plasma is stabilized against infernal modes; this allows the eITB to be reformed, as the steep increase of SXR signal shows (red middle trace, figure 2). During the formation of the barrier, we can observe the appearance of an MHD mode of resistive type (Mirnov coils, top red trace, figure 2). This is less disruptive than the ideal mode and 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(H_{RLW} drops) until the bottom of the oscillation; at this time the island begins to shrink, the confinement improves, and the cycle starts over. The resistive character, together with the slower growth rate of the mode, gives the smoother appearance to the oscillations, that nevertheless do not differ from the more ideal-type triggered cycles discussed before in terms of the effect on the eITB. The oscillations are then terminated by the ending of the heating phase at t=1.5s. The comparison of these different scenarios, from the more ideal to the more resistive, and their effect on confinement is the main scope of this paper.

2. Overview of the experiments

For discharge TCV #21653 (figure 1) the plasma current has been sustained by bootstrap and ECCD contribution [13]. Two gyrotrons off-axis (0.9MW) and one gyrotron on axis (0.45MW) were used. 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 1, with the steep increase in SXR emission [1]. The angle of injection of the on-axis launcher was varied, in order to tailor the current profile and to change the plasma pressure profile (-15^o for #21653, -4.5^o for #21655 reported in figure 3). The current profile for discharge #21655 has been reconstructed thanks to the Fokker-Planck code CQL3D (figure 3), resulting in a $q_{MIN} \approx 2.7$ at the radial location $\rho_\psi \simeq 0.5$, where the barrier is formed [7, 13]. For discharge #21653 this type of analysis is much more complicated by the fact that the last Thomson Scattering time point is 20ms before the crash, and the profile is still evolving. Magnetic signals analysis reveals the presence of MHD modes with periodicity m/n=3/1 and 2/1 during the disruption in #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 mode m/n=3/1 mode with a significant m/n=2/1 component, for β_N larger than 1. The β_N experimental value is close to unity, confirming that discharge #21655 is close to ideal stability threshold, with q_{MIN} near 3 (figure 4). The instability is caused by a high pressure gradient at $\rho_\psi \simeq 0.5$, where the eITB is formed in a low-shear region. This is the characteristic of infernal modes.

The value of q_{MIN} is important, as from the stability analysis it turns out that windows of stability exist between resonant integer numbers for the safety factor. This infernal mode appears in regions of low-shear. In this region the development of low-n

pressure-driven modes is possible, which was first described in [14] for reversed shear profiles. TCV plasmas are generally stable against the m/n=1/1 mode, as q_{MIN} is generally above the values for which the internal kink is unstable. Nevertheless, internal and external modes with m=2,3,4 develop when q_{MIN} is close to those integer values [7]. From the evolution of the H_{RLW} and the Thomson Scattering profiles, these modes

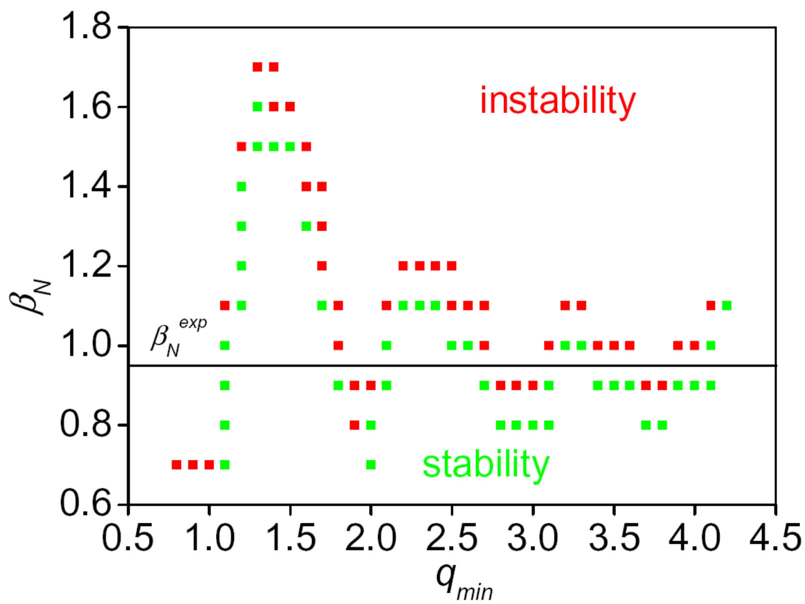

Figure 4: *The n=1 mode stability boundary plotted in q_{min} space. Green and red squares correspond to ideally stable and unstable configurations respectively. β_N^{exp} is plotted for TCV discharge #21655*

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. For $q_{MIN} > 4$, the infernal mode becomes an external kink mode, which is less sensitive to the values of q_{MIN} [7].

For TCV discharge #24696 (figure 1, green trace), the gyrotrons were fired with different timing and aims compared to the previously described experiments. 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 [10]. Thus, current and pressure profiles are different from the experiments described above, and ideal periodic modes develop. These have the character of sawtooth crashes, but the inversion radius is located close to the q=2 surface. This instability has been named Periodic Relaxation Oscillations (PROs) in [10, 11]. They are ideal kink-like and they are dominated by high local pressure gradient at the barrier location and global β limit. They resemble the so-called β-collapse observed in JT-60U [15]. By combined analysis between the pressure and current profiles, the destabilizing factor appears to be the peaked pressure gradient in conjunction with a low shear region. The latter is unavoidably near q_{MIN} with reverse shear profiles. Because of the phenomenology that accompanies them (diagnostic signatures) and the relationship to the strong pressure gradient, they can be ascribed to infernal modes. A fast, large crash of type m/n=2/1 at t=0.81s stops the initial fast growth of the eITB. The crash trigger a m/n=2/1 resistive mode that is stabilized later. At this time the confinement improves again

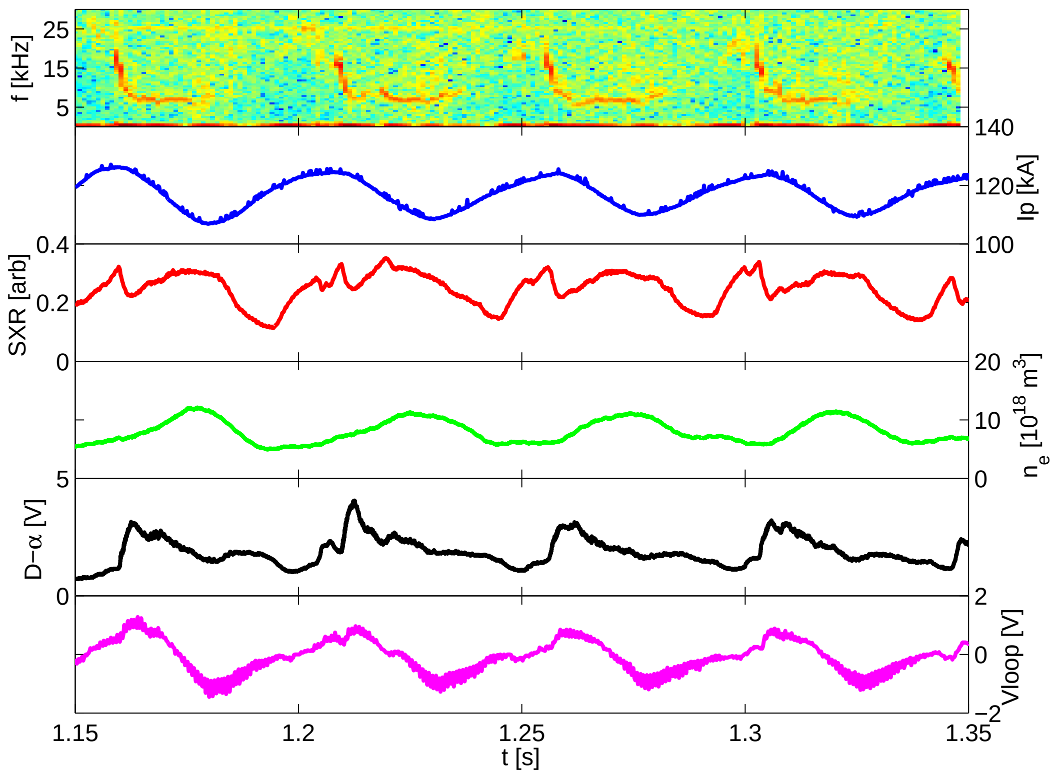

Figure 5: *Overview of regular mixed ideal-type and resistive instabilities, discharge TCV #32023. From the top: magnetic spectrogram, indicating the fast ideal phase followed by a resistive mode. Plasma current (blue) which reaches the top at the onset of the infernal modes. SXR radiation from the core (red), showing the crashes at the ideal event. Plasma density (green). D-α light (black).* V_{loop} *(magenta) showing the continuous changes in the magnetic configuration*

until the pressure gradient is strong enough to trigger another infernal mode, with a period $\tau \simeq$16ms, which is responsible for the absence of higher H_{RLW} for this discharge. The pressure peaking factor ($p_{e0}/\langle p_e \rangle$) reaches a very high value ($\simeq$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\simeq$10 and $\beta_N \simeq$0.75. If the plasma is taken further away from an ideal limit, resistive modes can be destabilized. These are generally less virulent than ideal modes, because they have a slower growth rate, and generally they saturate. This could allow plasma control to be put in place to detect and remove the modes from the plasma. The effect of confinement loss in the plasma is less strong, on a time scale comparable with that of the ideal modes. On the other hand, the integral effect can be as large as that of ideal modes, as resistive instabilities can prevent the eITB to be formed (or to reach the highest confinement) for times larger than 100ms. Thus, stabilization of resistive modes is as important as the avoidance of ideal ones. In order to describe resistive modes in presence of eITBs, two discharges with global plasma oscillations are described here-below (TCV #32023 and #32029). Due to the time scale of figure 2 it is not possible to appreciate the details

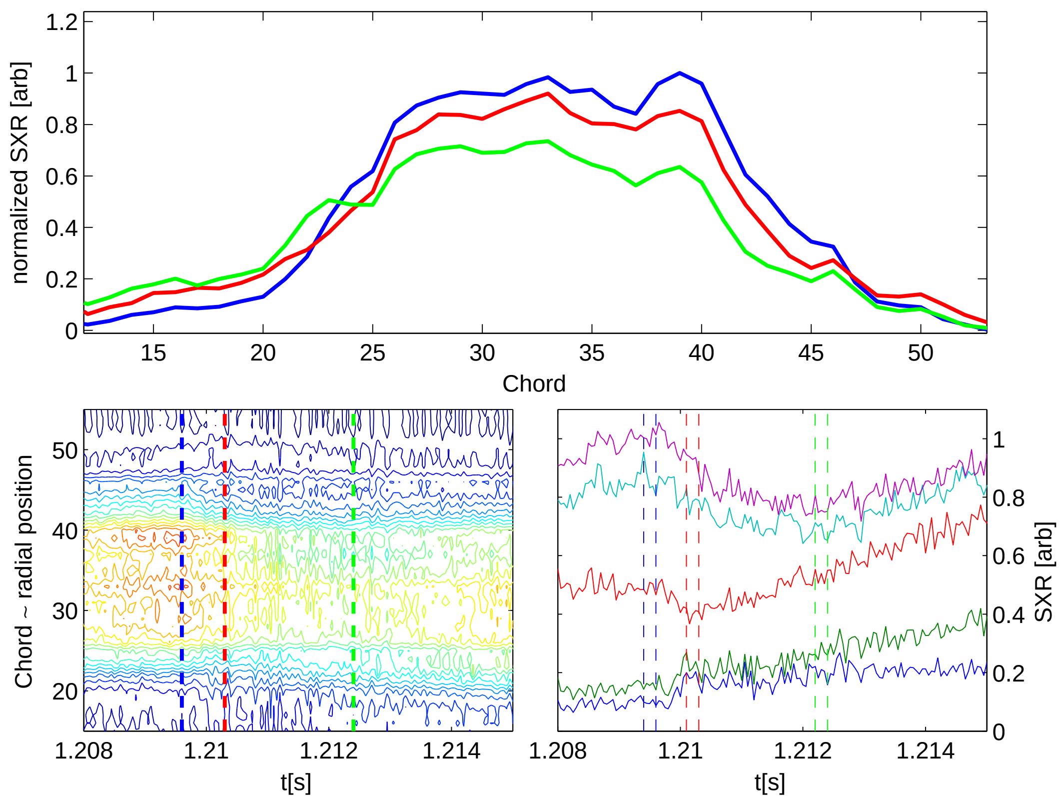

Figure 6: *TCV discharge #32023. Top plot shows the variation in the non-inverted SXR signal for the central 45 chords of DMPX. Bottom left plot shows the contour plot of the radiation dynamic and bottom right a selection of raw SXR signals. Three time windows are used to obtain the profiles: blue is pre-ideal crash mode, red is post-ideal crash mode and green during the secondary resistive mode*

of MHD modes, which are invariably present before and during the oscillatory regime. Discharge #32023 (blue trace) is characterized by regular small infernal mode crashes with frequency $f \simeq 20$Hz. 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 more triangular-like due to the ideal character. Figure 5 shows a selection of plasma parameters evolving during four events. The spectrogram of magnetic Mirnov signal (top trace) allows to appreciate the dual character of these oscillations. Every event is characterized by an ideal crash, which is responsible for the almost vertical signature indicating a large band of frequencies, from 15kHz to

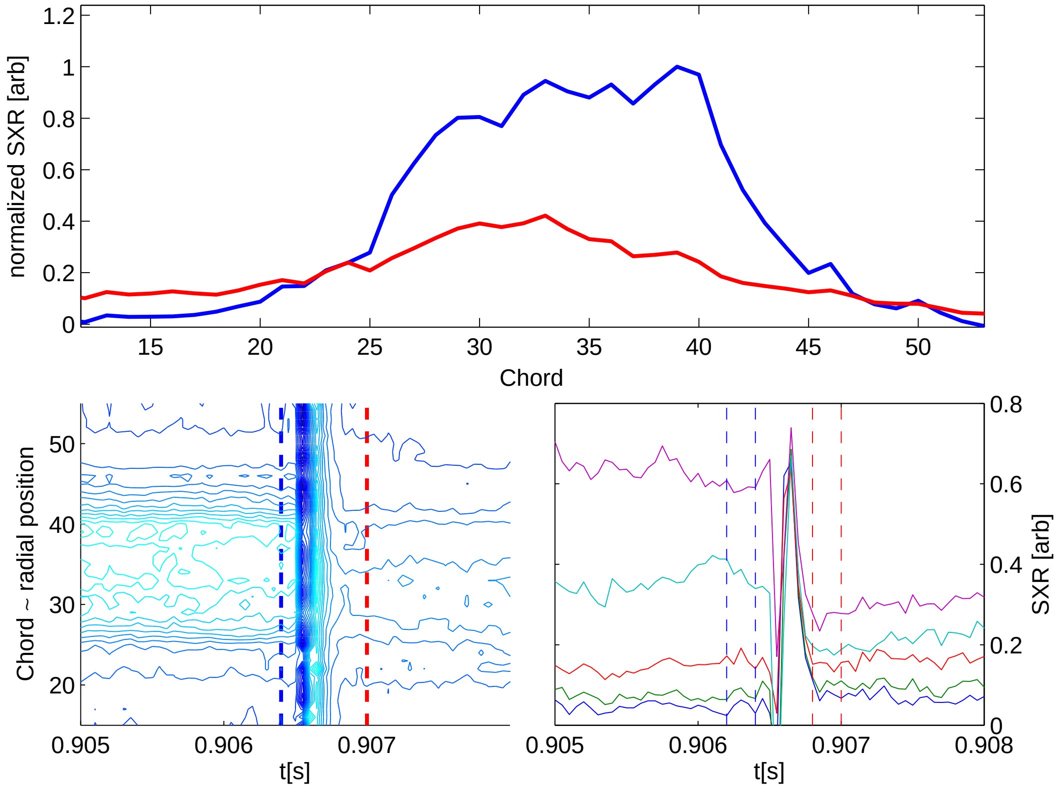

Figure 7: *TCV discharge #32029. Infernal mode analysis. The blue trace represents the pre-ideal state, the red one is post-ideal one. The reduction in radiation is about a factor of 2.5 indicating the great loss of confinement due to this ideal infernal mode*

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 has a resistive character and survives for Δt$\simeq$20ms. The magnetic island has a main periodicity m/n=2/1, which is also the main component of the ideal event. The plasma current (blue, second trace) shows oscillations (ΔI$\simeq$10kA) with the top of the current synchronous with the ideal mode triggering. 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* [5]. The V_{loop} follow the general behavior of the other traces, indicating the continuous evolution of the magnetic configuration during this oscillatory regime. Figure 6 refers to the first ideal event reported in figure 5. These modes are small infernal crashes, and their effect on the confinement is expected to be proportional to the size of the ideal event. Because of the limitation in the time points of the Thomson scattering system, it is more relevant to study the collapse with the aim of SXR radiation diagnostics. DMPX has a very high time and spatial resolution, and consist of a wire chamber located at the bottom of the vessel. The top plot in figure 6 shows the behavior of the radial line integrated emission of SXR just before (blue trace) and after the ideal event (red). The timing is reported in the bottom right trace, with the same color coding. Two vertical lines of the same colour indicates the time averaging used for the top plot. The drop in emission (proportional to the loss of confinement) is very limited (10% of the signal in the core). The green trace represents the time during which the secondary mode develops, indicating a larger drop in the signal. The bottom left plots shows a contour plot of the SXR chords, with the blue vertical line at the time of the maximum radiation emission. 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 is unique because it shows both type of modes in a distinctive way (figure 2, 0.8s$\leq$t$\leq$1s for the infernal mode unstable plasma, 1.2$\leq$t$\leq$1.5s for the resistive mode). At the time when the barrier is formed (t$\leq$0.8s) the electron temperature suddenly increases (fig. 2). We can infer the beginning of an extremely large global oscillation, with a full cycle completed before an ideal instability provokes the abrupt collapse of the temperature. The radiation profile before and after the crash shows the character of a sawtooth-like instability, with an inversion radius that is located in the proximity of what the plasma reconstruction code considers to be q=2. Based on the pressure profile and the phenomenology of the mode, the crash appears to be the result of a major infernal mode, just not large enough to disrupt the plasma as in #21653. It could be called a minor disruption or a β-collapse. In effect, it is a crash triggered by an ideal n=1 infernal mode. Another cycle begins afterwards, and this time at the top of an oscillation (t$\simeq$0.95s) the major crash is avoided and instead ideal-like *burtsy* modes begin. These tinier collapses (t$\geq$0.95s, black trace) are very frequent (Δt$\simeq$5ms) and accompanied by MHD oscillations (f$\simeq$15kHz); The effect of the modes on the confinement can be followed through the same SXR analysis as for #32023. The major crash is reported in figure 7. This time the loss of confinement appears much more relevant, with a loss of approximately 60% of the emissions in the core. The gradients at the barrier foot are lost and expulsion of particles and heat is evident. The base line of the SXR traces (from core to edge, bottom right) is almost identical after the crash, but the beginning of the positive slope is visible in the core trace (purple) after the crash. Indeed, thanks to the applied heating and the resilience of the plasma to the crash (a minor disruption, compared to the major one that terminates the plasma, #21653) the barrier is quickly reformed and the cycle begins again. Later on, after approximately 200ms, the ideal modes are stabilized. At t=1.22s the eITB begins to reform, which is accompanied by the development of a resistive NTM-like mode (figure 8, spectrogram trace at the top). The neoclassical character is inferred by the large bootstrap current fraction and is observed through

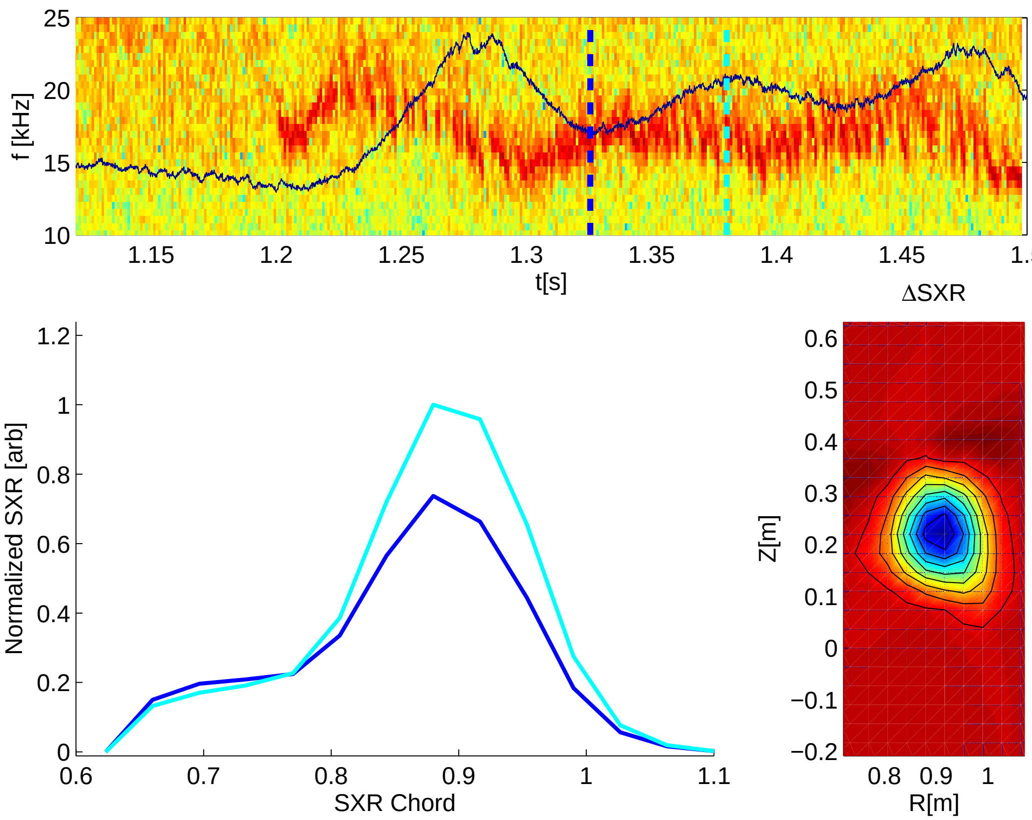

Figure 8: *TCV discharge #32029. NTM-like mode during an eITB. The top plot shows the spectrogram of a magnetic coil together with the SXR core trace (black) displaying the oscillation. The cyan time state is at the top of the oscillation (best confinement) and the blue represents the bottom. The profile (inverted SXR) indicates a drop in SXR radiation of approximately 25%. The tomography shows the* Δ_{SXR} *for the two phases.*

the evolution in time of the magnetic island width. 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 m/n=2/1 character. The stabilization of the ideal mode allows the formation of the eITBs, which, due to the changed plasma conditions, does not reach the highest confinement values as in the earlier stage. This, on the other hand, prevents the plasma from becoming infernal-unstable. The two SXR inverted traces (XTOMO diagnostic) are snapshots of the emission at the magnetic axis of the plasma at t=1.325s and t=1.38s, i.e. the top and the bottom of one large oscillation. The blue trace represents the minimum confinement phase; the island has reached the saturation size, and it is stabilized. This allows the electron temperature gradient to be re-established. The cyan trace is at a maximum of confinement; at this time the island begins to grow again, and the eITB gradient is being partly lost because of the plasma mixing between the outside and the inside of the barrier favored by the location of the NTM. The tomography shows the Δ-SXR between the two phases, indicating the cooling in the core provoked by the saturating island. The drop of SXR emission between the two phases is approximately 25%. Because of the MHD mixed character in this discharge, the effect of the island on the frequency of the NTM is less evident and clear than in other discharges dominated by the resistive character. Indeed in case of pure resistive behavior, the highest frequency is reached at the top of confinement, when the seeding island has a minimum size (generally below 1.5cm). The frequency tends to diminish as soon as the NTM character becomes relevant, and the island grows [3].

The MHD modes presented in all the discharges have main periodicity m/n=2/1, except for the ideal crash in 21653 which is mainly a m/n=3/1; the localization of the mode and therefore of the rational surface within the plasma is more complicated for the fully non inductive discharges. Due to current limitations in the hardware of the SXR systems (XTOMO and DMPX) the acquisition was performed at f=10kHz only, and the mode signal is almost buried in the noise. For these discharges we can only rely on magnetic data, which are capable of discriminating the mode numbers, but fail to describe the location (in R,Z). This is possible instead for #32023, where the island grows at the foot of the eITB during the decay phase, from $\simeq$1 to 3cm in width.

3. Conclusions

The role of MHD stability and control is of central importance for the development of steady state eITBs in tokamak plasmas. Values of H_{RLW} higher than 4 have been obtained during eITBs discharges, with and without the development of MHD instabilities. In the first case, a variety of phenomenology is encountered depending on the fine details of (mainly) the plasma current density and pressure profiles; This in turns depend on the heating and current drive strategy, and on the dynamic of the plasma evolution. The modes can be of ideal type (disruptions, infernal modes, PROs, ILMs) or resistive (tearing modes, NTMs), and all the intermediate states are possible. Because of the similarity in the value of q_{MIN}, most of the discharges presented have modes with main periodicity m/n=2/1. This, together with the observation of the transition between different phases of a single discharge, and different discharges with similar character, allows to state that the mode at the origin is the same one, and can have a more ideal or more resistive character depending on where the plasma stands in the stability space.

The origin of these modes is the unfavorable conjunction of large pressure gradient in a low shear region, that is infernal mode character as first described in [6]. 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, β-collapse, q=2 sawteeth, PRO, O-regime, minor and major disruptions in reverse shear are all related to the nearby stability limit of infernal modes. This is why they are sensitive to q_{MIN}, $p_0/<p>$, p' and shear [6].

The effect of all these modes is detrimental for the barrier, and therefore is against the goal of a steady-state high-performance plasma. 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 tuning the current and heat injection, hence by changing the current density and pressure profiles to avoid the proximity to rational integers of the safety factor 2 and 3.

Regarding the resistive modes, although their effect is less abrupt, the integral effect 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 or with local ECCD. Experiments with Ohmic contribution and current injection to prove this principle have been successfully achieved and they will be the scope of a later publication.

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