Global stability and MHD dynamics in TCV negative triangularity plasmas

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Negative triangularity tokamak (NTT) plasmas are the subject of increasing interest both in existing experiments and in view of fusion demonstration reactors. Experimental results indicate that negative triangularity plasmas keep L-mode edge characteristics while achieving improved core performance and confinement with respect to positive triangularity. An L-mode edge implies absence of Edge Localized Modes, making the NTT reactor an appealing concept. On the TCV device negative triangularity is studied since the 1990s [1] and recent experiments have further characterized a variety of scenarios with record performance in terms of normalized β [2]. MHD activity not necessarily leading to discharge termination is observed, in many cases from initial phases and related to n=1 [neoclassical] tearing modes. Global MHD stability of these plasmas is investigated with parametric numerical studies, to confirm the experimental evidence suggesting that most of the disruptive shots terminate below the eventual β limit. The numerical analysis, carried out with the linear resistive MHD stability code MARS-F[3], shows that triangularity does not influence the stability threshold of the ideal external kink mode. This is mostly influenced by the details of the current profile, parametrized by the presence of a minimum in the safety factor and its value, or more in general by the internal inductance. As an example, the n=1 ideal kink has been studied numerically for shots 69273 (limited, $\delta < 0$) and 69511 (limited, $\delta > 0$). In the calculation a set of equilibria are solved with the CHEASE

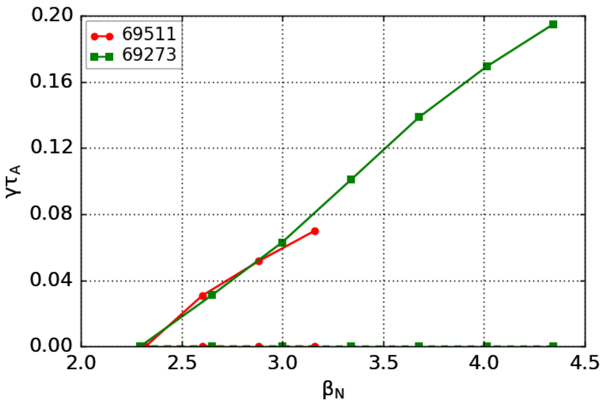

Figure 1 - Eigenvalue of most unstable n=1 ideal mode with varying plasma pressure

[1] See author list of H. Reimerdes et al 2022 Nucl. Fusion 62 042018

[4] code with varying pressure profile magnitude, while keeping shape and current. Only the modes resonant with $q > 1$ rational surfaces are considered, in order to study the external kink. For each re-scaled equilibrium the most unstable eigenmode is found by solving the (ideal) linear MHD eigenvalue problem with a vacuum region surrounding the plasma and ideal wall boundary conditions at infinity. The aforementioned results can be appreciated in Figure 1, where the normalized growth rate of the n=1 ideal kink is plotted against normalized β. For both these shots the experimental β_N values are below the calculated stability limit ($\beta_N \sim 2.3$) for external kink modes. On the other hand these cases both show sawtoothing behavior and the analyzed equilibria contain a q=1 rational surface, leading to a dominant m=1/n=1 unstable mode with internal kink structure. Recent experimental campaigns investigated the MHD phenomenology and dynamics in negative triangularity with elevated safety factor. In shot #73995 the plasma vertical position is varied between Z = 10 cm and Z = 0 cm, with co-ECCD (Electron Cyclotron Current Drive) moving from on-axis to off-axis. As reported in Figure 2, a mode with odd toroidal number appears during the sweep around$\sim 5\ kHz$. Two snapshots have been modelled to investigate the nature of this mode, taking equilibria respectively at t=0.8 s and t=1.3 s. In the ideal MHD framework #73995 and other similar shots yield results comparable to those shown in Figure 1, with stability thresholds for n=1 external kinks within the range $\beta_N = 2.2 \div 2.4$.

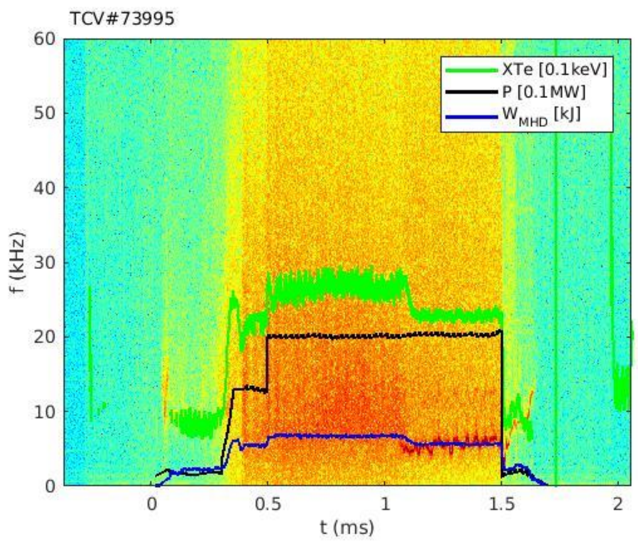

Figure 2 - Spectrogram of odd-n modes for shot #73995

<u>Resistive instabilities</u> have also been investigated for #73995 in the two selected instants, with a Spitzer model implemented for plasma resistivity $\eta \sim T_e^{-3/2}$. In the limit of $\beta \to 0$ the equilibria are rather similar and an n=1 unstable mode is found. The Tearing Mode scaling law $\gamma \sim \eta^{3/5}$ is almost perfectly recovered, with a slight modification at high η values where the growth rates bend towards the resistive kink scaling $\gamma \sim \eta^{1/3}$. This is reported for example in the left-hand plot of Figure 3 (red circles) for the equilibrium at t=1.3 s. In these plots the on-axis Lundquist number ($S = {}^{1}/_{\eta}$) is used as a proxy to vary the whole resistivity profile. When the full equilibrium pressure is retained in the stability calculation, stabilizing effects at high

Lundquist number are recovered. This stabilizing contribution, often referred to as the *Glasser-Greene-Johnson effect*, is driven by pressure and toroidal curvature [5]. Stabilization of the mode eventually occurs at $S > 1 \times 10^7$ for the first time snapshot and $S > 2 \times 10^7$ for the second. This result is shown in the right-hand part of Figure 3 where the curves of $\gamma\tau_A(S)$ are compared for the two times. The reported behavior finds a match in the experiment when looking at the first case, where the corresponding experimental Lundquist number is above the predicted threshold. The second snapshot on the other hand (t=1.3 s) almost overlaps the experimental number.

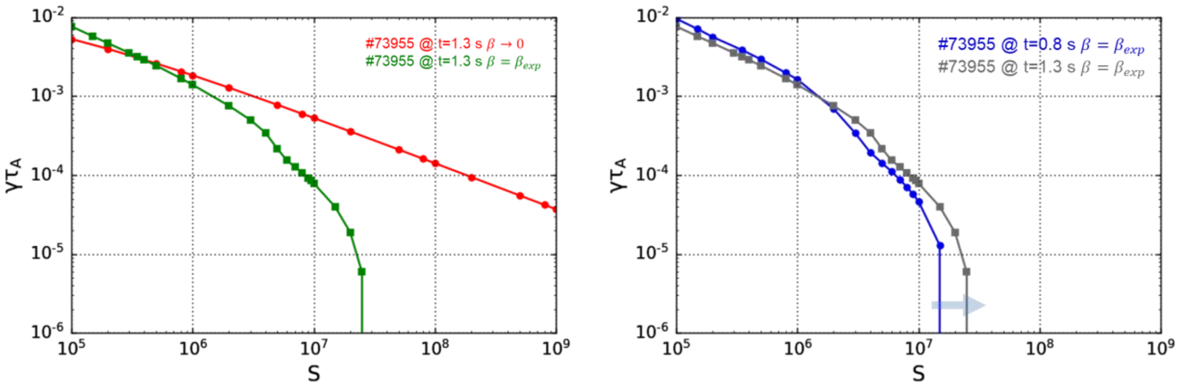

Figure 3 - Growth rate of n=1 tearing mode scaling with Lundquist number S. [Left] comparison between $\boldsymbol{\beta} \rightarrow 0$ limit (red circles) and full experimental pressure (green squares) for t=1.3 s. [Right] Comparison between t=0.8 s and t=1.3 s both including effects of pressure.

The result could be improved by tuning numerical resolution and/or input experimental data. Nevertheless the model successfully captures the behavior of the mode which is more unstable at t=1.3 s with respect to the earlier time point. By looking at the spatial structure and poloidal Fourier components of the mode eigenfunction at t=1.3 s we can see that the behavior is dominated by the q=2 rational surface with a main m=2 component. This can be appreciated left part of Figure 4. A comparison with the experiment can be made by looking at the electron temperature measurements in the considered time windows. Figure 4 shows on the right the temperature profiles obtained by Thomson scattering, where a flattening is clearly visible for t=1.3 s around the location of the q=2 surface. **Discussion and outlook**: Preliminary analysis of recent experimental results and comparison with linear MHD modeling indicate that negative triangularity does not significantly affect the structure and dynamics of ideal modes. For the internal kink for example this is in agreement with recent numerical investigations [6] [7] although the interplay of such modes with energetic particles or the effect of resistivity have not been considered. Interestingly enough the stability threshold of pressure-driven external kinks are also found similar when modeling comparable equilibria with positive or negative average triangularity. In order to perform a more detailed analysis, mode structure and stability shall be correlated with the triangularity of the dominant resonant surface.

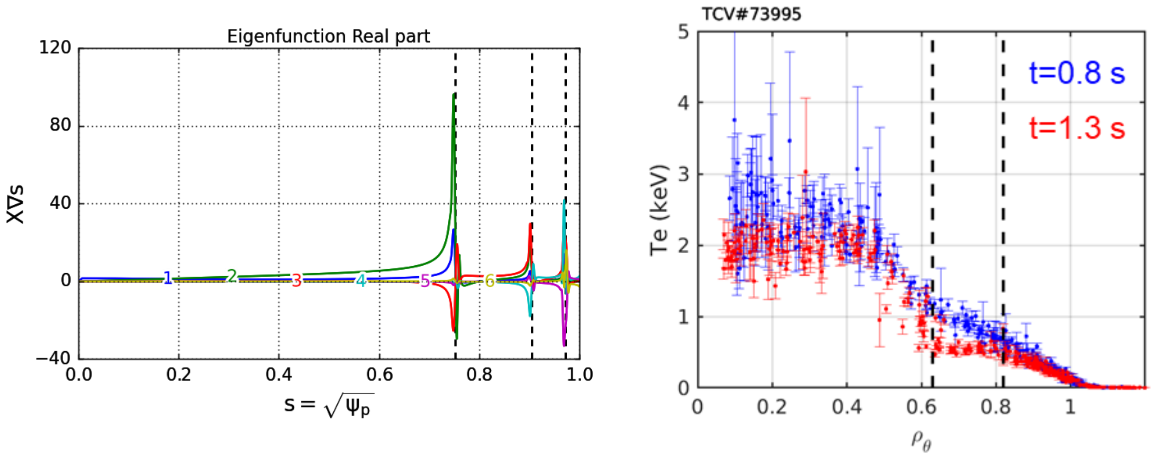

Figure 4 – [Left] Eigenfunction of n=1 tearing mode close to experimental Lundquist number, the radial component (real part) of plasma displacement is plotted against $s = \rho_\theta$ (poloidal flux coordinate). [Right] Electron temperature measurements (Thomson scattering) around t=0.8 s and t=1.3 s.

In other words considering the radial profile of $\delta(s)$ could explain the observations and modeling results. Many of the analyzed shots show a coherent unstable n=1 mode starting right from the beginning of the discharge. Often identified as tearing modes, this seems to be confirmed by the modeling carried out, recovering well the expected behavior of classical tearing modes, which then appear saturated in the experiments. For one of the presented cases the MARS-F calculation is in good agreement with evidence of stabilization/destabilization of the mode. Similar results are found when studying the scaling of the growth rate with β_N instead of S, which is another viable way to investigate how the mode stabilized with pressure. While similar calculations have found mode frequency to become important at some point [8], this effect has not been recovered in the present work. This effect will be further analyzed in future work. A comparison case with positive triangularity has not been considered yet for the last part of the presented analysis, this will be useful to assess the effect of δ on modes that are located on outer rational surfaces.

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