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The Peeling-Ballooning Model Revisited

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The edge-localized modes (ELMs) which typically occur in the high confinement mode (H-mode) of tokamak plasmas are generally regarded as resulting from large-scale magneto-hydro-dynamical (MHD) instabilities [1].

Within ideal MHD, two basic instabilities are associated with the edge transport barrier: ballooning modes with high toroidal mode number n which are driven by the edge pressure gradient and low-n peeling and kink modes (hereafter simply referred to as peeling modes for brevity) which are driven by a finite edge current density and current density gradients. Both instabilities can couple to form intermediate-n peeling-ballooning modes [2] which may be responsible for type-I ELMs. These latter modes are driven by both the edge pressure gradient and the current.

We study the peeling-ballooning model for Edge Localized Models (ELMs) in experimental discharges with respect to the stability properties of peeling modes in the plasma edge. Several authors [3, 4] have found strong or even complete stabilization of the peeling mode within ideal magnetohydrodynamics (MHD) if the separatrix is included in the analysis. Close to marginal stability, the peeling mode is unstable with a rational flux surface just outside the plasma boundary while a rational flux surface just inside the plasma is stabilizing. Furthermore, finite currents and large current gradients which drive the peeling mode are typically very sensitive to the exact position of the separatrix with respect to experimental pressure and current profiles. A finite resistivity, due to increased collisionality in the plasma edge, however, may be destabilizing for the peeling mode and lead to a so-called 'peeling-tearing mode' which has been shown by [4] for an $n = 1$ kink.

We extend the analysis to both peeling as well as coupled peeling-ballooning modes at higher toroidal mode numbers $n \leq 15$ by means of linear MHD stability studies using the linear MHD stability code `ILSA`. The `ILSA` code has recently been created from the `MISHKA` [5] and `CASTOR_FLOW` [6] codes as part of the Integrated Tokamak Modelling effort.

Starting from various ASDEX Upgrade ELMy H-mode discharges, we calculate free boundary

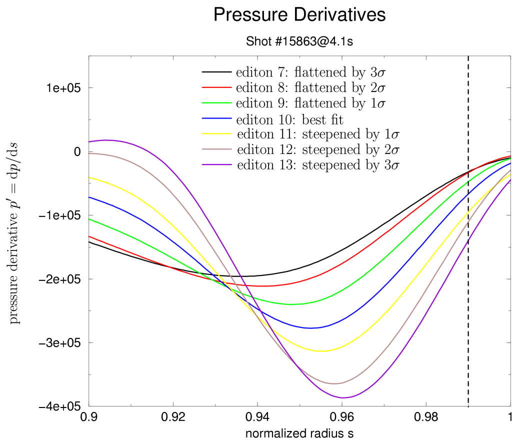

Figure 1: Edge pressure derivatives

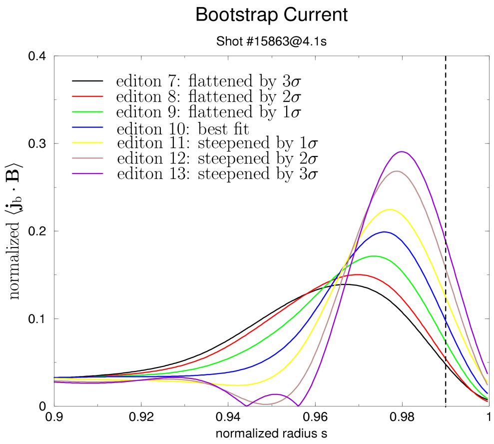

Figure 2: Bootstrap current density

equilibria after carefully determining the separatrix position from power balance considerations. The equilibria are then reduced to fixed boundary equilibria by placing the plasma boundary inside the separatrix and cutting the edge plasma profiles rather than compressing them onto the reduced radial domain.

We analyze four ELMy shot instances at ASDEX Upgrade: shot #15863 at 4.1s (type II ELMs), shot #15865 at 5.027s (mixed type I and II), and shot #20116 at 2.25s and 5.09s (both type I). For all four cases, the temperature and density profiles which were used to calculate self-consistent bootstrap current equilibria with the free boundary equilibrium code `CLISTE` were varied within experimental error bars. Fig. 1 and 2 show the pressure derivatives and the corresponding flux surface averaged and normalized bootstrap current densities in the plasma edge for shot #15863. As expected the cases with steeper edge pressure gradient show a stronger bootstrap current, thereby having a stronger drive for both ballooning and peeling modes.

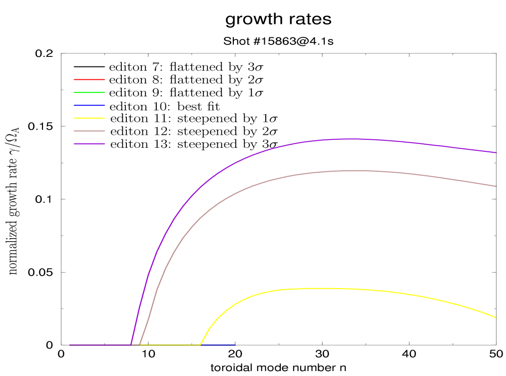

Figure 3: linear growth rates γ/Ω_A

The effect can be seen in the normalized linear growth rates γ/Ω_A of the driven MHD modes (Fig. 3). Only the steepened profiles are unstable with a growth rate rising with the steepness of the pressure gradient.

Clearly, both pressure gradients and edge currents drive the MHD modes unstable. A closer analysis of the radial mode structure supports the picture of a coupled peeling-ballooning mode which is strongly localized at the plasma edge. Figs. 4 and 5 show the mode structure of the linear eigenfunction for the steepest pressure profile. The poloidal mode number *m* is given for the strongest mode.

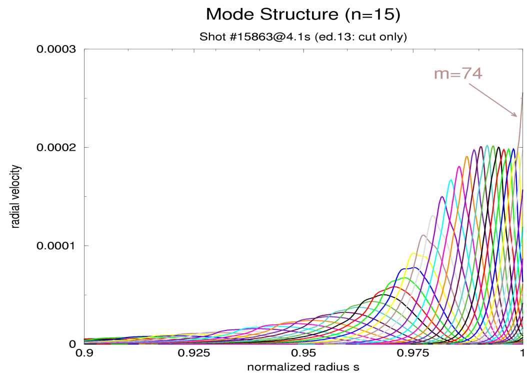

Figure 4: profiles cut at cutting point

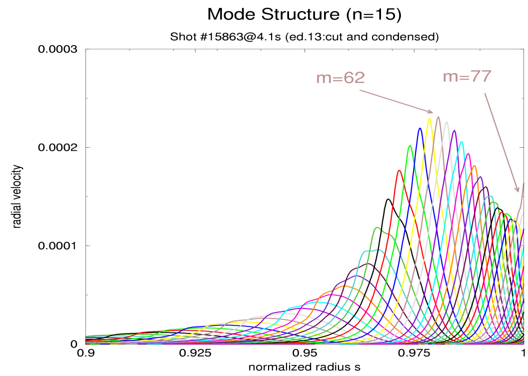

Figure 5: profiles condensed

The cases presented here differ in the way the equilibrium for the stability analysis is calculated. The calculation follows two commonly used methods. In the first case (Fig. 4), the free boundary equilibrium is cut at a certain closed flux surface close to the separatrix with a fraction ψ_{bd} of the poloidal flux at the separatrix. Here, all profiles are cut respectively, thereby changing the pressure gradient p' and the current density at the plasma boundary when ψ_{bd} is varied. The dashed line in Figs. 1 and 2 indicates the innermost cutoff position of our study at $\psi_{bd} = s^2 = 0.98$. In the second case (Fig. 5), only the plasma shape is influenced by the cut while the pressure and current profiles are condensed to fit into the reduced radial domain, thereby maintaining the drive for the peeling-ballooning modes in the plasma edge.

The removal of the open flux region from the equilibrium calculations is necessary for linear stability calculations with `ILSA` because of the singularity in field aligned coordinate systems at the separatrix. The growth rates shown in Fig. 3 refer to equilibria which were cut at $\psi_{bd} = 0.98$. The difference between the two methods mostly appears in the importance of the peeling drive which is given by the relative amplitude of the current density and its gradient at the plasma boundary. This is smaller for the latter case, therefore leading to a smaller contribution of the peeling component of the mode.

To study the influence of the presence of an X-point on the stability of the peeling-ballooning mode we conducted a series of studies where we modified the cutoff position ψ_{bd} in a range from 0.98 to 0.9999. Great emphasis was laid upon the convergence of both the equilibrium and the stability calculations.

Within ideal MHD, we expect the peeling component of the unstable modes to become stabilized by the increasing q-shear at the plasma edge as we move the cutoff point ψ_{bd} closer to the separatrix. For $\psi_{bd} = 1$ all rational flux surfaces lie inside the plasma boundary, thereby stabilizing the peeling component.

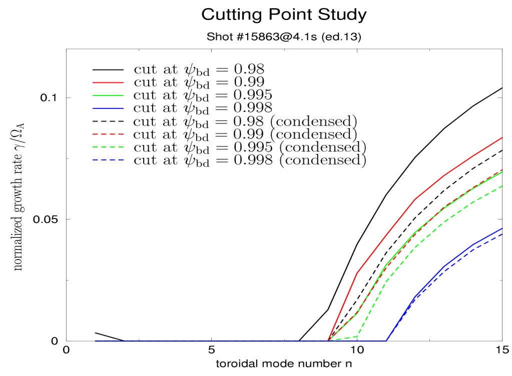

Figure 6: linear growth rates γ/Ω_A for the cutting study

Fig. 6 shows the normalized linear growth rates of the peeling-ballooning modes for a series of cutoff positions for both methods. As expected, the two methods converge to the same growth rate as ψ_{bd} approaches unity. For both methods, the growth rates decrease with increasing ψ_{bd} until the modes finally become stabilized for $\psi_{bd} \geq 0.999$. The other investigated shot instances yield a similar result with full stabilization of the peeling- or peeling-ballooning modes around $\psi_{bd} = 0.999$.

Since the stabilization is independent of the chosen method for the equilibrium calculation it is clear that the increasing q-shear towards the plasma edge must be the cause for this effect. This conforms with the expectation that ideal peeling modes become stabilized close to marginal stability by increasing the shear in the plasma edge. It remains to be clarified how this result is affected by the presence of a resistive plasma layer in the vicinity of the separatrix. For experimental temperature profiles, the resistive skin depth for the diamagnetic drift frequency ω_{*i} can be up to 5 mm depending on the poloidal mode number m. Resistive effects allowing for magnetic reconnection can then drive a resistive peeling-tearing mode unstable [4].

Our results show that the presence of an X-point in a peeling-ballooning unstable equilibrium at marginal stability leads to the full stabilization of the peeling component of the mode which may stabilize the equilibrium altogether. Our current studies focus on the ballooning threshold for the analyzed shots. It remains to be clarified how much steeper the edge pressure has to be to yield linear growth rates which converge to a finite value as ψ_{bd} goes to unity, i.e., to determine the pressure gradient threshold for peeling-ballooning modes in the presence of an X-point.

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