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Linear Edge Stability Analysis for Bootstrap Current Equilibria at ASDEX Upgrade

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Edge Stability for Bootstrap Current Equilibria

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-hydrodynamical (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 modes which are driven by the edge current. 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. However, at the plasma edge, the flux surface averaged parallel current density is often dominated by the bootstrap current which depends on the pressure and temperature gradients, as well as the collisionality. In the pedestal of an H-mode plasma, the pressure gradient therefore acts as a twofold drive for coupled peeling-ballooning modes.

The work presented here is part of a larger effort to discriminate between type-I and type-II ELMs based on ASDEX Upgrade discharges. A correct treatment of the bootstrap current when calculating experimental equilibria is essential for a detailed analysis of their linear MHD stability properties.

The CLISTE free boundary equilibrium code has been extended to include self-consistent constraints for the bootstrap current at the plasma edge following the Sauter model [3]. Based on the new bootstrap current equilibria calculated with CLISTE, an adapted version of the HELENA equilibrium code generates high-precision fixed-boundary equilibria which are then used as input to the linear MHD stability solvers MISHKA [4], CASTOR_FLOW [5], and ELITE [2, 6]. As part of the Integrated Tokamak Modelling effort (IMP 1), the MISHKA and MISHKA_D

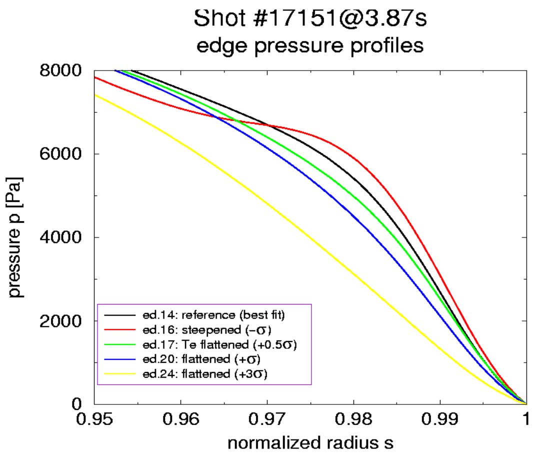

Figure 1: Edge pressure profiles

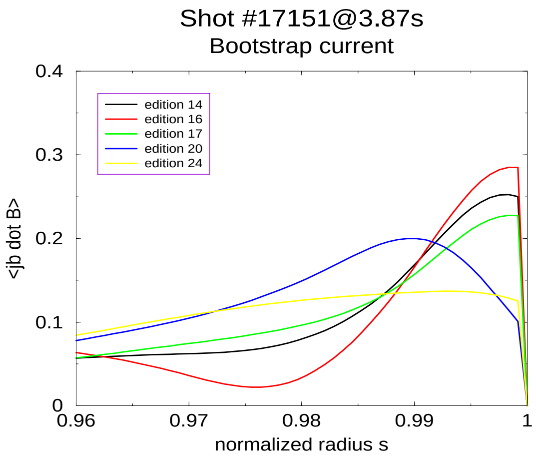

Figure 2: Bootstrap current density

codes have been updated and integrated into the CASTOR_FLOW code, thus creating a linear stability code with a wide range of applications including ideal and resistive MHD, toroidal and poloidal flows, resistive wall modes and external perturbations.

The ideal MHD (MISHKA) mode of the CASTOR_FLOW code has been used to study the linear stability properties of a series of bootstrap current equilibria based on a type-I ELMy H-mode shot (#17151@3.87s) at ASDEX Upgrade. The equilibria have been generated by a systematic variation of the pedestal width about the best fit to the experimental data. Fig. 1 shows the edge pressure profiles for the various equilibria where edition 14 is the best-fit reference scenario.

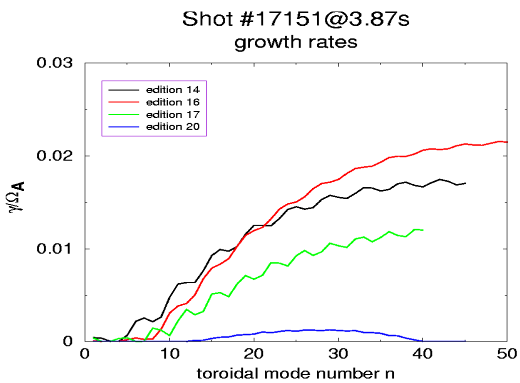

Figure 3: linear growth rates γ/Ω_A

The corresponding flux surface averaged bootstrap current densities $\langle \mathbf{j}_b \cdot \mathbf{B} \rangle$ are shown in Fig. 2. The cases with steep edge pressure gradients (14, 16, 17) exhibit a strong localized bootstrap current at the plasma edge while the flatter cases (20, 24) show only small and less localized bootstrap contributions.

Among the analyzed cases, editions 14 through 20 are linearly unstable while edition 24 does not exhibit any instability. The respective growth rates are shown in Fig. 3 as normalized to the Alfvén frequency Ω_A.

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. Fig. 4 shows the mode structure of the linear

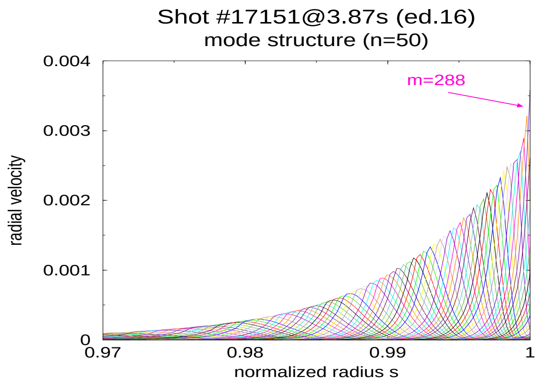

Figure 4: high edge current density

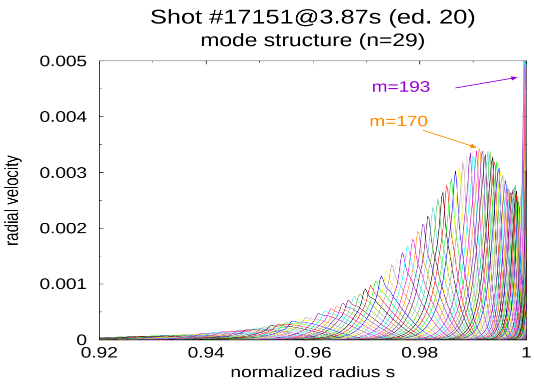

Figure 5: low edge current density

eigenfunction for the case with strong bootstrap currents at the edge (edition 16). The poloidal mode number m is given for the strongest mode. The mode shows a clear peeling character in its localization at the plasma boundary but is also driven by the edge pressure gradient.

Fig. 5 on the other hand shows the mode structure for the case with low edge current density where the bootstrap current is localized somewhat inward of the plasma edge (edition 20). The mode structure is characteristic for a peeling-ballooning mode with $m = 170$ the maximum poloidal mode of the ballooning part and $m = 193$ the maximum poloidal mode of the peeling part. While the eigenmodes for the remaining cases with strong bootstrap edge currents (editions 14 and 17) strongly resemble the peeling case (edition 16), the removal of the bootstrap current from the edge causes the transition to a coupled peeling-ballooning mode. Because of the smaller pressure gradient this mode is much weaker than the more peeling-like modes.

In the recent past, peeling modes as a potential candidate for ELMs have come under debate since their stability properties are strongly affected by X-point geometry [1, 7]. The results presented here stem from linear ideal MHD studies for a lower single-null equilibrium where the separatrix and X-point have been removed by cutting the free boundary equilibrium at 98% of the poloidal flux at the separatrix. For such a fixed boundary equilibrium, the influence of the positions of the last rational surface in the plasma and the first rational surface outside the plasma with respect to the position of the edge current density becomes visible in the beat structure of the growth rates vs. the toroidal mode number (*Fig. 3*). This is not the case for the peeling-ballooning mode in edition 20.

Although the exact effect of the X-point geometry on the stability properties of the analyzed equilibrium remains to be checked in the future, our studies demonstrate the importance of a proper treatment of the edge current density - even if the X-point is included in the analysis.

Linear Stability with Toroidal Flows

In order to study the influence of toroidal flows on the linear stability of tokamak equilibria, the CASTOR and ELITE codes have been extended to allow for sheared toroidal flows [5, 8]. Fig. 6 shows a benchmark of the CASTOR_FLOW and the ELITE codes for an edge ballooning unstable circular symmetric equilibrium. The linear growth rate γ/Ω_A is shown for various toroidal mode numbers n vs. the on-axis rotation frequency Ω_0. The rotational shear follows the profile $\Omega(\psi) = \Omega_0(1-\psi^3)$ where ψ denotes the normalized poloidal flux.

We find excellent agreement for low to intermediate toroidal mode numbers and moderate deviations for high mode numbers. It also becomes clear that rotational shear can have stabilizing as well as destabilizing effects on the plasma, depending on both toroidal mode number and rotation frequencies. A more detailed analysis of the effects of sheared toroidal rotation on ELMs based on actual tokamak equilibria is part of the ongoing effort to understand the linear stability properties of H-mode plasmas. Ultimately, the focus has to be moved on to the non-linear studies to understand particle transport and heat flows during ELMs [7].

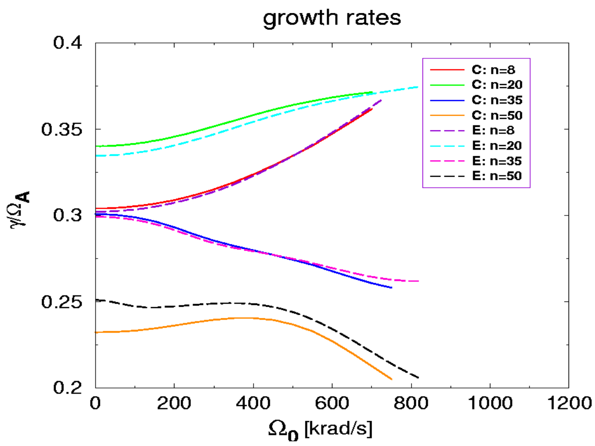

Figure 6: linear growth rates γ/Ω_A including sheared toroidal rotation

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