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Cross-Machine and Cross-Code Comparisons in Linear MHD Stability Analysis for Tokamaks

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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-hydrodynamical (MHD) instabilities [1]. Within ideal MHD, instabilities associated with the edge transport barrier can either be driven by the edge pressure gradient (ballooning modes with high toroidal mode number n), a finite current density gradient in the edge (general peeling or edge kink modes with low n) or a finite current density at the plasma boundary (pure peeling modes with low n). They 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.

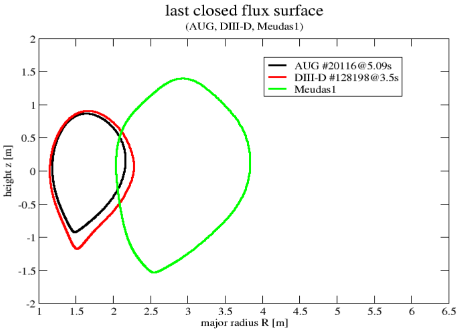

Figure 1: Last closed flux surfaces for the studied equilibria

A recent extension of the fixed boundary equilibrium code HELENA [3] allows computation of high resolution fixed boundary equilibria for linear magnetohydrodynamics (MHD) stability analysis starting from the widely used G-EQDSK equilibrium format, which is for instance produced by the free boundary equilibrium code EFIT. With this tool at hand, we perform linear ideal MHD edge stability analyses for equilibria of ELMy H-mode shots at DIII-D and ASDEX Upgrade as well as a MEUDAS [4] generated model equilibrium with focus on the validity of the peeling-ballooning model [2] for Edge Localized Modes (ELMs).

Recent work [5] suggests strong stabilization of the peeling and kink modes within ideal MHD near a separatrix. Since the linear MHD stability codes ILSA [6, 7], ELITE [2, 8], and MARG2D [9, 10], used for this analysis, exclude the separatrix from their computational do-

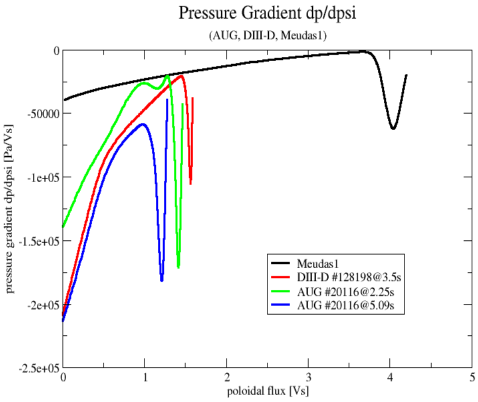

Figure 2: Edge pressure gradients

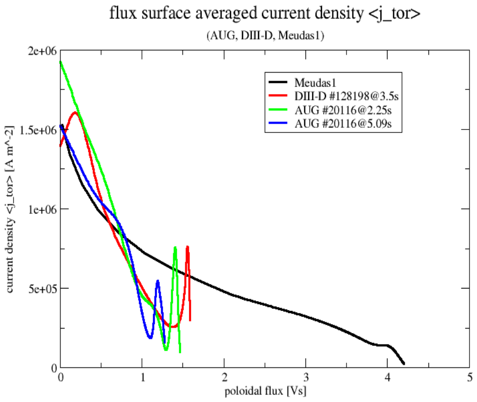

Figure 3: Edge current densities

main, due to a coordinate singularity at the X-point of diverted tokamak equilibria, we investigate the effect of X-point geometry on the stability of the peeling-ballooning mode by carefully placing the plasma boundary inside the separatrix and cutting the edge plasma profiles rather than compressing them onto the reduced radial domain. The radial cut-off position is then varied to range from 99.0% to 99.8% of the poloidal flux at the separatrix, thereby approaching X-point geometry.

Fig. 1 shows the last closed flux surfaces (for a cutoff position at 99.8%) for the equilibria analyzed in this contribution. These equilibria which are all linearly MHD unstable differ by the amplitudes of their edge pressure gradient and edge current density (Figs. 2 and 3). The edge current density in Fig. 3 has been calculated from the converged HELENA equilibria and line averaged along the flux surfaces and is consistent with the bootstrap current for the experimental cases (AUG and DIII-D). The experimental cases were selected from a series of confinement scans in DIII-D and AUG [11].

By inspection of the profiles, the relative amplitude of the pressure gradient compared to the edge current peak is significantly larger for the two AUG time slices and the Meudas1 case

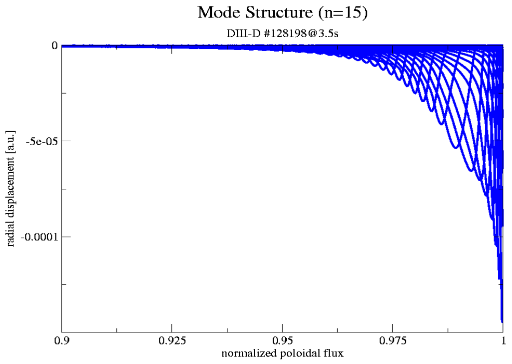

Figure 4: Mode structure n=15

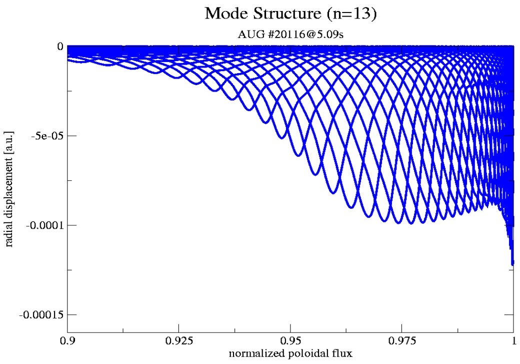

Figure 5: Mode structure n=13

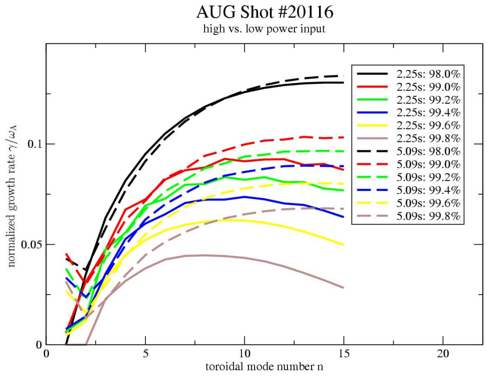

Figure 6: Cutoff scan for AUG #20116

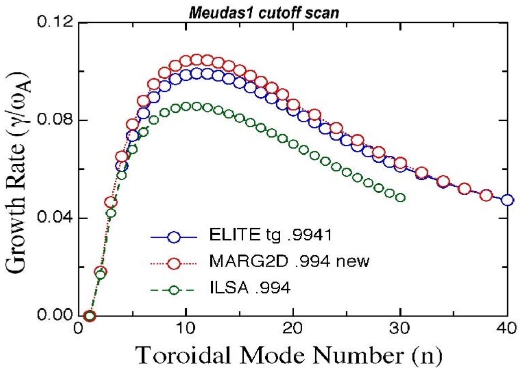

Figure 7: Code benchmark for Meudas1

than for the DIII-D shot. The two AUG time slices differ mostly by their edge current densities. We therefore expect a stronger peeling character of the edge instability in the DIII-D case than in the other cases (Figs. 4 and 5). For the Meudas1 and AUG cases, we find a distinctive peeling-ballooning mode while the mode of the DIII-D case is closer to an external kink mode. A detailed comparison of the two time slices of AUG #20116 shows that the higher input power leads to a more pronounced ballooning component of the edge mode through the relative gain of the pressure gradient over the edge current density.

This result also shows in the spectrum of the growth rates γ normalized to the Alfvén frequency ω_A vs. the toroidal mode number n as depicted in Fig. 6. For the case with stronger pressure gradient drive (time slice at 5.09 s) the spectrum peaks at higher toroidal mode numbers as is expected for more ballooning-like peeling-ballooning modes.

Fig. 6 also shows the decrease of the overall growth rate with the cutoff position ψ_{bd}, i.e., with increase of the q-shear at the edge. This indicates a stabilizing influence of the q-shear on the pure peeling as well as the kink mode. While we expect complete stabilization of the finite edge current driven pure peeling mode in ideal MHD as we approach the separatrix, the behaviour of the edge kink mode in the vicinity of an X-point remains unclear.

For a better understanding of this behaviour we have started to carry out cross-code benchmarks on various machines. Fig. 7 shows the spectrum of growth rates for the Meudas1 case as found by the stability codes ILSA, ELITE, and MARG2D. The plasma is treated as an ideal MHD fluid with no compression. We find excellent qualitative and reasonable quantitative agreement between all three codes where the shift between the ILSA and ELITE/MARG2D results is currently being investigated.

Figs. 8 and 9 show the normalized growth rates γ/ω_A for a cutoff scan for the DIII-D shot #128198@3.5s and the AUG shot #20116@2.25s as calculated with ELITE and ILSA in ideal, compressionless MHD. The oscillations in 9 indicate the strong peeling/kink character of the

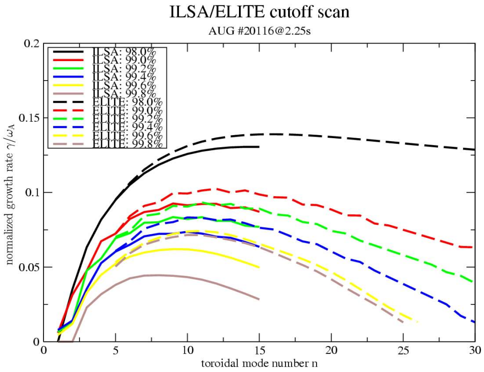

Figure 8: Code benchmark for AUG

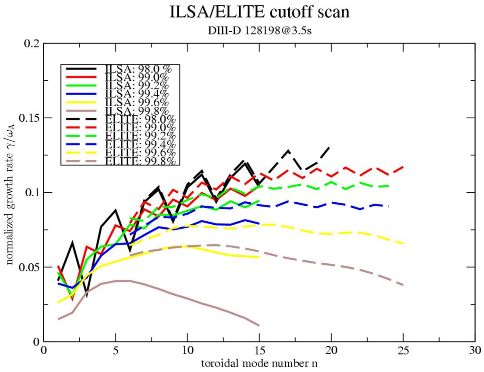

Figure 9: Code benchmark for DIII-D

modes whose stability is influenced by the distance of the plasma boundary from the nearest rational flux surface - which varies with the toroidal mode number n. For the inner cutoff points (from 98.0% to 99.4%), we find very good qualitative agreement between ILSA and ELITE and reasonable quantitative agreement. The outermost cutoff points (99.6% and 99.8%) disagree even qualitatively because of a lack of numerical resolution for this high q-shear region. For 99.8% the assumptions of MHD break down since gyroeffects become important. For either case we find a decreasing growth rate with increasing ψ_{bd} which is at least partially due to the reduction of the edge current density. Future studies will investigate the influence of the increased q-shear on the general peeling mode by use of equilibria with zero current density at the plasma boundary.

Generally, the influence of the cutoff position on the stability threshold is expected to be small because of the rapid increase of the growth rates with increasing pressure gradient and current drives. This dependence of the stability boundary - especially with respect to the edge current profiles - will be investigated in the near future.

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