MHD Stability Analysis of ASDEX Upgrade H-mode Plasmas in Various ELMy and ELM-Free Regimes
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Introduction

The Edge Localised Modes (ELMs) affect detrimentally divertors by eroding them with temporally peaked energy and particle fluxes. For ITER it is necessary to operate in a regime where the damaging ELMs are avoided.

In this work, we study the MHD stability of various ELM and ELM-like regimes of ASDEX Upgrade tokamak using the ELM model given by Connor et al. [1], where ELMs are triggered by coupled low- to intermediate-n peeling-ballooning modes. The observed edge behaviour can be explained by the changes in the stability properties.

Equilibrium Reconstruction and Stability analysis

We reconstruct the equilibria using experimental temperature and density profiles to obtain the pressure profiles. Also the bootstrap current profile is evaluated from these profiles using the formula given by Sauter et al. [2].

We analyse the low- to intermediate-n peeling-ballooning mode stability using the ideal MHD code GATO [3]. To achieve sufficient convergence, the grid size (radial points times poloidal points) is \(N_r \times N_\chi = 200 \times 400\) for \(n=3\) and \(N_r \times N_\chi = 300 \times 600\) for \(n=8\). In the high-n ballooning stability, we use IDBALL.

Type II ELMs

An earlier stability analysis showed that the large type I ELMs in ASDEX Upgrade are triggered by bootstrap current driven peeling-ballooning instability [4]. When type I ELMy conditions are changed to correspond the type II (high triangularity, high \(q_{95}\), high density and almost double null configuration), the radial width of the ELM triggering instability becomes narrower and the instability requires higher edge bootstrap current to be destabilised. Assuming that an ELM crash removes plasma proportionally to its radial width, the stabilisation against the low-n modes and the narrower mode width of the intermediate-n modes can explain the smaller ELM size.

Pellet Triggered ELMs

Pellets can be used to trigger ELMs [5]. We analyse the stability of the pellet triggered ELMs and compare it with the intrinsic ELMs. In the equilibrium reconstruction we use the experimental temperature and density profiles, published in Ref. [5].

The ballooning stability analysis results of the edge are shown in Fig. 1. There is a marked difference between the reference case with large intrinsic 3 Hz compound ELMs compared with the intrinsic 20 Hz ELMs and pellet triggered ELMs. In the 3 Hz ELM case, the normalised pedestal pressure gradient \(\alpha = 2Rq_2(dp/dr)/B^2\) is limited by the tip of the ballooning stability boundary. A slight decrease in the shear would take it to the second stability region. The other two cases are deep in the 2nd stable region. Thus, their pressure gradient is not limited by the ballooning modes.

In the analysis of low-n peeling-ballooning modes, we find that only the intrinsic 20 Hz ELM plasma is in unstable region. The pellet triggered case is stable but becomes unstable when the edge current is increased by 20 %. The intrinsic 3 Hz ELM plasma is not destabilised even by a 50 % increase in edge current.

Combining the low- and high-n mode results, we can conclude that the edge of the
intrinsic 3 Hz plasma is limited by the ballooning mode stability. The bootstrap current can not grow sufficiently to destabilise the peeling-ballooning mode and trigger an ELM. It can be assumed that prior to an ELM, the plasma gains access to the 2\textsuperscript{nd} stable region allowing the bootstrap current to grow and destabilise the low-n peeling-ballooning mode.

The other two cases are deep in the 2\textsuperscript{nd} stable region and, thus, their pressure gradient is limited only by transport. As the bootstrap current builds up, the 20 Hz intrinsic ELMy plasma reaches the peeling mode boundary thus triggering an ELM. The pellet triggered does not reach the low-n mode boundary even with fully included bootstrap current.

However, the pellets can cause local perturbations that destabilise the edge plasma when it is already close to the stability limit.

**Quiescent H-mode** At low density, stationary H-modes with complete ELM suppression are obtained in ASDEX Upgrade with counter-injected beams, high plasma clearance from the walls and low recycling conditions\cite{6}\cite{7}. The typical plasma profiles for a QHM and ELMy H-mode discharge are shown in Fig. 2. The electron temperatures are almost identical, density is higher in ELMy H-mode than in QHM and ion temperature is higher in QHM. Since there are no edge Thomson scattering measurements, the edge profiles are adjusted so that they give the same pressure gradient at the edge for both cases. This is done so that the stability differences can be investigated. In the actual experiment, the pressure gradients are not necessarily equal. The $Z_{\text{eff}}$ profile is assumed flat. The line-integrated value of 5 is used for QHM and 2.5 for the ELMy H-mode that correspond the values observed in ASDEX Upgrade 2002 campaign \cite{6}. It must be noted, however, that recently QHM discharges with significantly lower $Z_{\text{eff}}$ (typically below 3) have been achieved in ASDEX Upgrade \cite{7}.

The profiles used in the equilibrium reconstruction are shown in Fig. 2. The plasma shapes of the equilibria are identical and taken from the ASDEX Upgrade discharge \#16104 at 2.5s. The edge pressure gradient and the bootstrap current profile are shown in Fig. 3. Note that even though the pressure gradients are almost the same, the bootstrap current in QHM is significantly smaller. This is due to two factors. First, the high $Z_{\text{eff}}$ reduces the current in QHM. Secondly, $\nabla T_i$ (responsible for high pedestal pressure in QHM) drives bootstrap current less effectively than $\nabla T_e$ or $\nabla n_e$.

We find the stability boundary for the ELMy H-mode and QHM by scaling the
temperature profiles until the plasmas become unstable. Figure 4 shows the growth rate of $n=3$ peeling-ballooning mode as a function of the maximum value of normalised pressure gradient $\alpha$ for both plasmas. The stability boundaries (in $\alpha$) are the same for $n=8$, but lower mode numbers, like $n=1$ are more stable.

The reason for the significantly higher stable edge pressure gradient in QHM is the smaller edge bootstrap current. In equilibrium reconstruction using magnetic measurements [7], no difference has been found in the edge current between the ELMy and QHM phase within one shot. However, this is not necessarily in contradiction with the above, since the difference shown in Fig. 3 is within the margin of error. As seen in Fig. 4, even this reduction in current has a relatively large stabilising effect on the peeling-ballooning modes.

Both QHM and ELMy H-mode have access to 2nd stability of the $n=\infty$ ballooning modes in the steepest pressure gradient region. Only at the very edge, $\rho > 0.99$ does QHM become 1st stability limited due to the low edge current, while the ELMy H-mode stays in the 2nd stability.
The QHM has been achieved in smaller plasmas than what is typical in H-mode in ASDEX Upgrade. A minor radius of 50 cm is used instead of 53 cm in typical ELMy H-modes. The high clearance has some effect on where the ill-confined neutral beam ions hit on the wall, but it also has a direct effect on the plasma stability. When increasing minor radius with fixed total current, the bootstrap current contribution becomes larger and, consequently, the current profile becomes wider with higher edge current. This destabilises the low-\(n\) modes. The effect of the size variation is shown in Fig. 5.

The changes in the QHM plasma conditions seem to improve the edge stability against low-\(n\) peeling-balloonng modes, the most likely triggers for ELMs. The improved edge stability explains why no ELMs are triggered in QHM even with the same pedestal pressure as in ELMy H-mode. However, the observed \(n=1\) mode during QHM is not explained by these changes.

**Edge Stabilisation by High \(\beta_p\)**

In high triangularity discharges in JT-60U, the edge region stability improved when the global \(\beta_p\) was increased [8]. We study the effect of \(\beta_p\) on the edge stability by starting from an ordinary H-mode plasma and then artificially increasing the core pressure while keeping the edge unchanged.

The stability analysis results are shown in Fig 6. An increase in \(\beta_p\) increases the Shafranov shift. This in turn squeezes the flux surfaces on the low field side. The low field side current decreases, and the low-\(n\) peeling-balloonng mode becomes stabilised. This allows to increase the edge pressure gradient to a higher value before an ELM is triggered. If \(\beta_p\) is increased even further, a global mode appears. As seen in Fig. 6, the stabilisation is reduced with low triangularity.

**Conclusions**

The stability analysis of various ELMy and ELM-like edge plasmas show that the changes in edge stability against low-\(n\) peeling-balloonng modes and \(n=\infty\) ballooning modes can explain the observed changes in the ELM behaviour.

The recent results seem to contradict with the idea of the ELM suppression in QHM due to the reduced bootstrap current by high \(Z_{eff}\). Still even without the effect from \(Z_{eff}\), the bootstrap current could be smaller in QHM than in ELMy H-mode for the same pressure gradient due to the fact the ion temperature gradient (QHM) drives the bootstrap current less effectively than density gradient (ELMy H-mode).

**References**