THE PHYSICS OF ELM-FREE REGIMES IN EUROFUSION TOKAMAKS
Pedestal tailoring via ballooning modes

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1. INTRODUCTION

The development of operational scenarios without large Type-I ELMs is of utmost importance for the stable operation and longevity of future tokamaks. To this end, one of the most important research topics at the moment is the search for robust ELM-free regimes with sufficient confinement to support a fusion reactor. The EUROfusion tokamak exploitation program has therefore made the understanding of ELM-free regimes a major topic of exploration across all its contributing devices (ASDEX Upgrade, JET, MAST-Upgrade, TCV, and WEST). An integrated program to investigate a range of Type-I ELM-free regimes has been developed covering the enhanced D-alpha (EDA), magnetic perturbations (MP), negative triangularity (NT), quasi-continuous exhaust (QCE), quiescent H-mode (QH), the baseline small ELMs (SE), and X-point radiator (XPR) regimes.

This contribution will detail the latest results from all of these regimes, but focus on the well-developed understanding of NT[1, 2, 3] and QCE plasmas[4, 5]. The highlight of these efforts is the development and exploration of NT and QCE scenarios in JET, enabled via predictive modelling, and the comparison of the two regimes at similar engineering parameters of 1.5 MA and 20 MW of NBI heating; both NT and QCE plasmas could be realised at good confinement, though the QCE also had significantly higher core density. The demonstration of these two regimes in JET is an important milestone for fusion energy as it paves the way for robust large-ELM-free operation in future devices. The combination of experimental scenario development and predictive modelling indicate that the QCE, at least, is likely to be a default operational regime in future devices, such as ITER, SPARC, and DEMO.

2. THE PHYSICS PICTURE OF TYPE-I ELM AVOIDANCE

Large ELM avoidance can be understood by considering the EPED framework, sketched as the red lines in figure 1. The pedestal gradient is limited by a transport mechanism (dashed lines), often considered to be a KBM, while the overall pedestal structure is limited by the onset of a global peeling-ballooning mode (solid lines). There are then two main categories of large-ELM avoidance: one applies to e.g. QCE and QH mode, where the Type-I ELM stability limit is raised (e.g. via increased plasma shaping) and additional transport is created via an MHD mode. This corresponds to the green lines in figure 1. A second type reduces both stability limits significantly, to the point where the H-mode is no longer accessed, as is the case in NT plasmas, corresponding to the blue lines in figure 1.

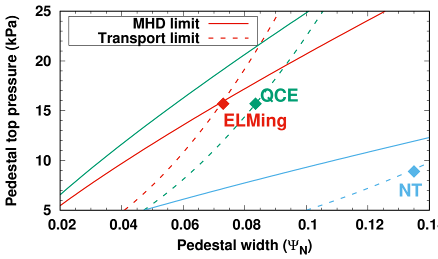

FIG. 1. Schematic of Type-I ELM avoidance for QCE and NT plasmas

The task of understanding ELM-free regimes is then one of understanding the additional transport mechanisms. Ballooning modes have been shown to play the dominant role in NT[2] and QCE[6] plasmas. In the case of NT, H-mode avoidance has been linked with blocking access to the second stable region in s-α space[2]. Access to the QCE is linked to an unstable ballooning mode localised at the separatrix, independently of the structure of the rest of the pedestal (which may tend towards low-, medium-, or high-n modes). A helically localised ballooning mode has also been observed in MP plasmas in AUG[7], though island creation via MPs blocking the pedestal widening is also a candidate to explain ELM suppression[8]. QH-mode plasmas are well understood in the MHD framework, but rely on a saturated kink/peeling mode to provide extra transport.

3. THE STEPLADDER APPROACH TO ELM-FREE REGIMES

The highlight of experiments and modelling efforts in the last years has been the implementation of a step-ladder approach to understanding the EDA, QCE, and NT on mid-sized tokamaks (particularly TCV and AUG) and developing them in JET during its final campaign. Recent understanding of the operational space of the QCE from the separatrix parameters[4, 9] and MHD stability[6, 10] helped guide the development of the QCE in JET[11]; a sufficiently high shaping parameter (defined as $\kappa^2(1+\delta)$, which should exceed 4.9 at JET) and a critical separatrix density which can be determined from machine parameters are the key requirements. The highlights of the JET experiments are low q_{95} (> 3.3), high power (> 20 MW) scenarios in both D and DT with pedestal top pressures consistent with the predictions from EPED-like pedestal modelling, as has also been observed in AUG. Interpretive pedestal analysis shows these plasmas close to the peeling-ballooning boundary. By performing QCE experiments on AUG, JET, and TCV, a promising trend of decreasing collisionality with increasing machine size is observed. The parameters achieved at JET, combined with predictive modelling, indicate that the QCE is likely to be a default operational regime in future devices such as ITER, SPARC, and DEMO.

The flexible shaping capabilities of TCV have helped drive the understanding of the separate elements of ELM-avoidance and confinement improvement in NT. TCV has reproduced the NT shapes developed on AUG and JET, and has validated the ELMing and ELM-avoidant behaviour seen on both of them. In the case of the JET shape, additional shaping scans at TCV to stronger negative shapes showed that, while the shaping requirements for ELM-avoidance were met, even more strongly shaped plasmas would have been necessary to see confinement improvement; this could not be tested due to limitations of the PF-coils at JET. NT and QCE could be compared at JET at 1.5 MA plasma current and NBI heating of 20 MW. Both of the large-ELM-free scenarios show comparably good confinement, though the density of the QCE is significantly higher.

4. SUMMARY AND CONCLUSIONS

The combined experiments described in this work have focused on performing detailed physics studies on smaller more flexible machines. While the full physics pictures (and potential reduced models) of some ELM-avoidance regimes are not currently available, progress is still being made on several devices towards the development and understanding of EDA, MP, and QH plasmas. However, the understanding gained from experiments on AUG and TCV has resulted in robust access-criterion models for both NT and QCE based on local ballooning stability. These models have been used to make predictions for JET, culminating in the development and exploration of these regimes on the (formerly) largest operating tokamak in the world. Experiments on all of these regimes will continue in an effort to define a robust large-ELM free operational scenario for the next generation of tokamaks.

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