Joint experiments tailoring the plasma evolution to maximise pedestal performance

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Abstract. The pedestal height has been significantly increased by optimising the plasma conditions at the point of access into H-mode in joint experiments in JET, MAST and TCV. Furthermore, analytic theory has been developed to explain the improved pedestal performance achieved by establishing high core pressure during the L-mode phase as well as a predictive pedestal model incorporating the core pressure self-consistently which yields good agreement with multi-machine empirical observations. By tailoring the core pressure before access to H-mode the pedestal height was increased compared to plasmas without evolution tailoring despite having otherwise identical plasma parameters. This improvement in pedestal height has been sustained for multiple ELM cycles in TCV, though further work is required to demonstrate the compatibility of this recipe with required ELM size and impurity control.

1. Introduction and Theory

The operational constraints of a metal wall, amongst which is increased gas injection to avoid damage to plasma facing components and tungsten accumulation, can impede achievement of the plasma energy confinement required for the ITER baseline scenario [1]. As well as jeopardising $Q = 10$ in ITER, these constraints obstruct the goals of the JET D-T campaign, which necessitate robust high confinement plasmas. Finding techniques to increase the pedestal height could significantly improve the achievable fusion gain. Consequently, experiments in JET, MAST and TCV have addressed methods to improve pedestal performance through discharge evolution tailoring.

A simplified cartoon of how to achieve an enhanced pedestal from constraints on peeling-ballooning stability is shown in figure 1. In this sketch, the "typical" plasma operational constraints result in H-modes with normalised pressure gradient well below the target pedestal parameters to achieve the requisite global confinement. This is typical in JET operation at high current with the ITER-like wall, where gas injection is required to protect the tungsten divertor, which increases collisionality and decreases the pedestal bootstrap current (the red evolution). If the divertor constraint is relaxed and the gas injection is reduced, one can achieve lower collisionality (following the green path) to achieve the target pedestal. This is typical of $H = 1$ plasmas in carbon-wall devices. In the event that higher collisionality results from constraints placed by the plasma facing components, there are two alternatives: Drive edge current to replace the bootstrap current, though this is difficult to achieve and often transient, or stabilising the ballooning modes such that a higher pressure gradient can be achieved before ELMs are triggered. In this paper we demonstrate that this is possible by increasing the core pressure. It should be noted that the presence of a high-field side high density front has also been postulated to affect pedestal confinement in metal-wall devices [2, 3]. For a fixed gas injection, the techniques discussed in this paper could partially alleviate the degradation of pedestal performance, though this has yet to be tested under conditions with high gas injection and large separation between density and temperature profiles in the pedestal region.

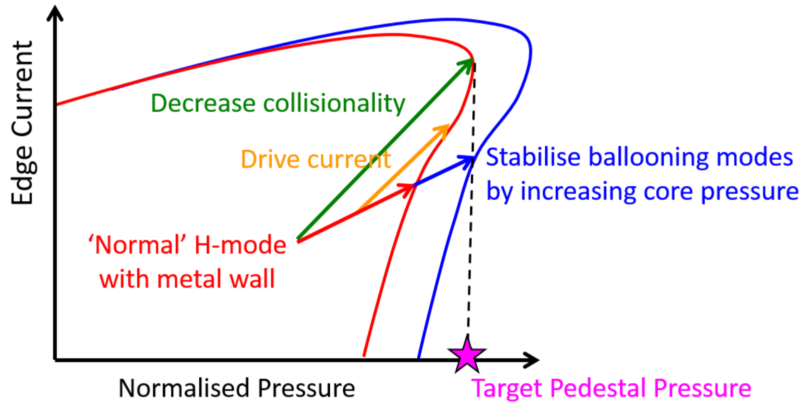

FIG. 1. Improved pedestals can be achieved by lowering collisionality, driving edge current or by increasing the critical pressure for triggering ballooning modes.

It is known that increasing the global plasma β stabilises ballooning modes [4], symptomatic of the observed increased pedestal height [5]. The effect of core pressure on ballooning stability has been investigated analytically [6]. Here, the core pressure effectively means the stored energy inside the plasma radius of the subsequent edge transport barrier top when the pedestal is formed, ie $\psi_N \leq 0.95$. An analytic equilibrium with a narrow steep pressure region was developed which included Shafranov Shift, plasma shaping and toroidicity. This $s-\alpha$ equilibrium was then used to provide the inputs for the ballooning equation. Low magnetic shear was assumed which allowed a two length scale approach. The resulting equations were averaged over the poloidal angle to produce an averaged ballooning equation. This equation was solved to find the ballooning stability boundaries. The stability diagrams are presented as universal curves for any toroidicity by appropriate scalings of parameters (to be more precise, these scale the various parameters relative to the stabilising magnetic well due to toroidicity) in figure 2. Ballooning stability was shown to improve with increasing core pressure through the effect of both Shafranov shift and ellipticity.

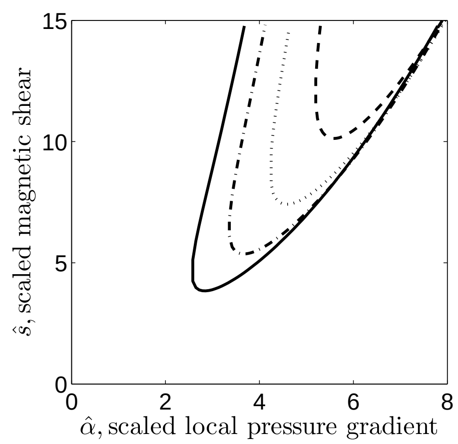

FIG. 2. Stability in the scaled $s-\alpha$ diagram as global pressure is increased; $\hat{\beta} = 0$ (solid line), $\hat{\beta} = 0.1$ (dash-dot line), $\hat{\beta} = 0.2$ (dotted line), and $\hat{\beta} = 0.3$ (dashed line). The plasma boundary has fixed ellipticity. The parameters are scaled to be independent of aspect ratio.

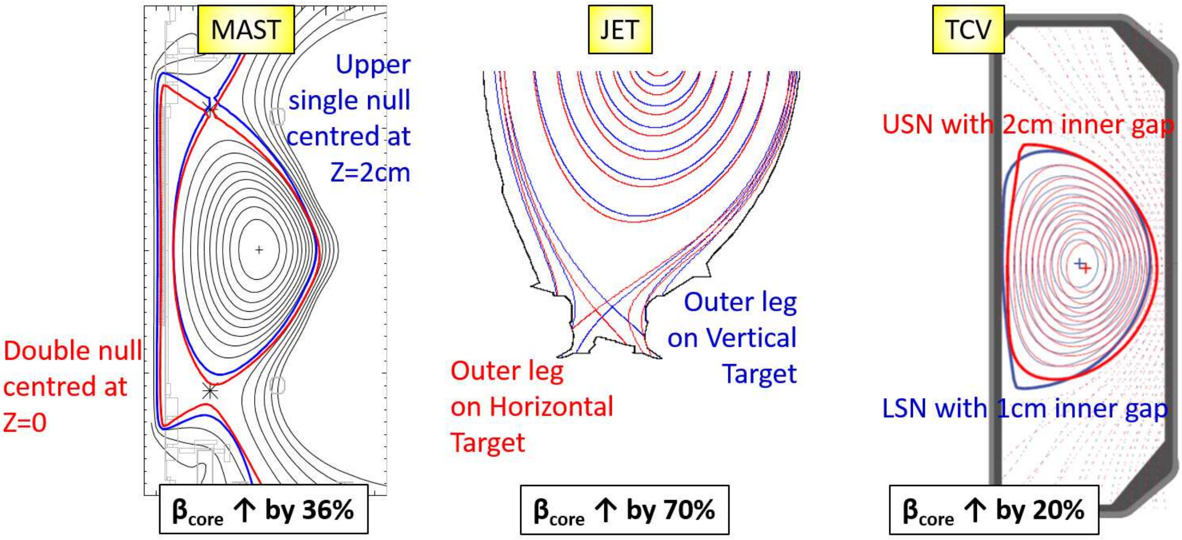

FIG. 3. Pairs of magnetic configurations in MAST, JET and TCV with small changes to the geometry but

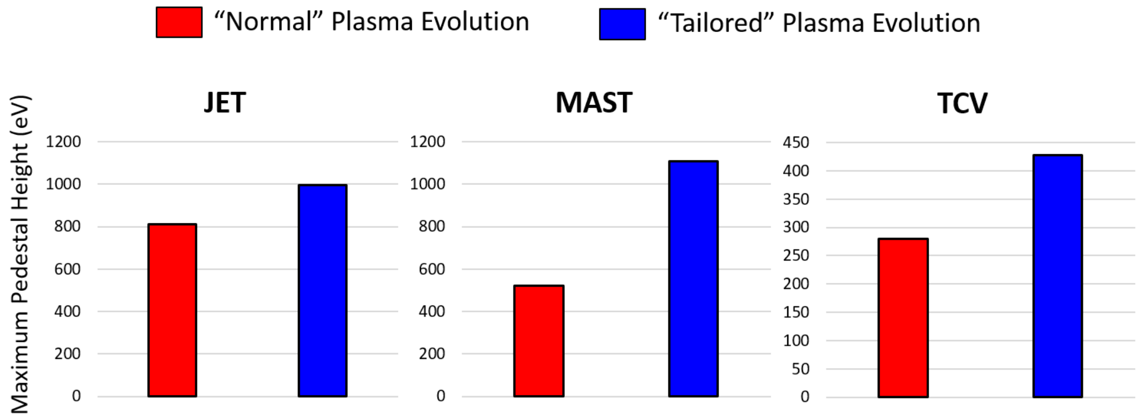

FIG. 4. The maximum achievable pedestal height in JET, MAST and TCV plasmas with tailored plasma evolution compared to "normal" H-mode plasmas with the same shaping, heating and engineering parameters

This paper demonstrates the causality that increasing the core pressure during the L-mode phase of the plasma evolution leads to an increased pedestal height in section 2. before comparing the improved pedestals with ab initio modelling in section 3. Furthermore, the improvement in pedestal can be sustained, as demonstrated on TCV in section 4. giving rise to positive indications of performance improvements possible in ITER, shown in section 5.

2. Pedestal improvement through evolution tailoring

It is possible to increase the core pressure in L-mode by deliberately suppressing the L-H transition before invoking a transition at a higher core pressure than the usual plasma evolution. This has been achieved in three different tokamaks by small changes to the magnetic geometry, as shown in figure 3.

In MAST, the plasma is moved vertically upwards by 2cm to an upper single null (USN) plasma. This increases the power required to access H-mode, P_{thr}, by at least a factor of two. Operating in USN allows the plasma to be heated to increase β_{core} whilst staying in L-mode, at which point the H-mode can be triggered instantly by moving the plasma back down to a balanced double null configuration centred on the geometric axis, under which condition the heating power is then significantly above P_{thr}. In JET the H-mode can be suppressed by operating with the outer divertor strike point on the vertical target, raising P_{thr} by 70% compared to operating on the horizontal target. Finally, in TCV the H-mode can be suppressed by operating with adverse ∇B drift and a 1cm inner gap compared to a comparable plasma with favourable ∇B drift and a 2cm inner gap.

In all cases the pessimal magnetic configuration is adopted to begin the discharge, with heating applied to the level just below P_{thr} to increase β_{core}. When the core pressure is saturated, the magnetic configuration is rapidly changed (in all cases in $<$ 50ms), at which point H-mode is accessed and the pedestal forms with a high initial core pressure. The core pressure stabilises the ballooning modes, as predicted analytically in section 1, meaning that the maximum pedestal height increases compared to a comparable plasma which begins in the optimal magnetic configuration and consequently has a lower β_{core} upon H-mode access, as shown in figure 4. It is possible to reach hotter pedestals even without evolution tailoring, as achieved for instance in β scans in reference [7], but this typically involves operating with increased power or lower field and current, which are not options in ITER.

3. Comparison of enhanced pedestal in experiments with predictive modelling

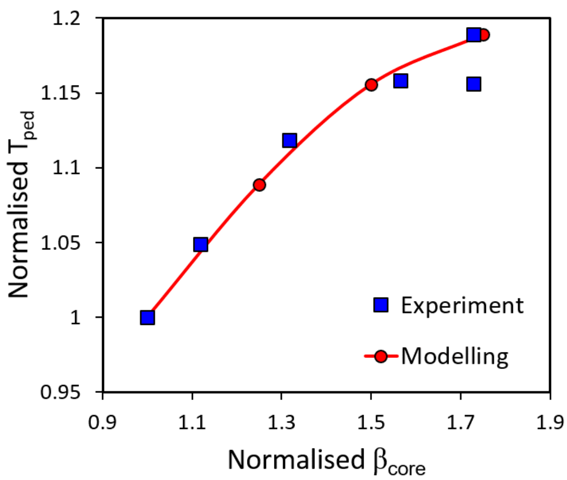

FIG. 5. Normalised improvement in pedestal height against the normalised core pressure at L-H transition comparing JET data with predictive modelling

A predictive modelling framework has been developed which negates the need to specify the global β *a priori* and core density as input, as is the case with EPED [8]. The Europed predictive pedestal model [9] is coupled to the JINTRAC integrated modelling code in an iterative loop until the pedestal structure converges, using as constraint the core pressure from JETTO transport simulations. This predictive framework has been applied to model the achievable pedestals given a range of initial conditions and compared against the empirical data. Figure 5 shows the achievable pedestal height as a function of the core pressure in JET experiments compared to predictive modelling. In both cases, the pedestal temperature and core pressure is normalised to the "normal" plasma conditions when the plasma evolution tailoring described in section 2 is not applied. The predictive modelling performed before the experiment indicated that the 70% increase in core pressure achievable from evolution tailoring would support a 19% increase in the maximum pedestal temperature. This is in excellent agreement with the observed empirical trend from JET experiments where the core pressure is increased in L-mode by deliberately suppressing the L-H transition by tailoring the divertor configuration.

In both MAST and TCV, there are also sizeable increases in the pedestal height as the core pressure is increased, as seen in figure 6. Indeed, the increase in the pedestal height from evolution tailoring is self-perpetuating, since the higher pedestal supports a larger core pressure, which further stabilises the ballooning modes. This can be observed in figure 6 where the difference in β at the L-H transition and that at the first ELM is seen to widen as the initial core pressure at H-mode access increases.

Whilst there is excellent agreement between the observed pedestal in JET with an ITER-like metal wall and the predictive modelling, this is not the case in MAST and TCV with a carbon wall. In both cases, the experimentally observed pedestal height is much larger than those predicted ab initio. For larger global β, the pedestal height before the first ELM increases, explained by an increase in the pedestal pressure gradient needed to drive ballooning modes unstable for higher core pressure. An ancillary stabilisation arises in MAST as the ballooning limit is increased to a higher pressure gradient by the higher core β since this increases the ELM period [10]. Longer ELM periods allow more impurity ingress which changes the Z_{eff} and dilutes the ion density, allowing a further increase in the pedestal temperature. In this way, the overall fusion performance can be improved by increasing the core pressure, since this allows the establishment of a higher pedestal, which in turn facilitates an even more elevated core pressure until reaching the point allowable by core stability and turbulence limits [11]. In the MAST plasmas reported here the ultimate performance is limited by core MHD at high core pressure ($\beta_N \sim 4$).

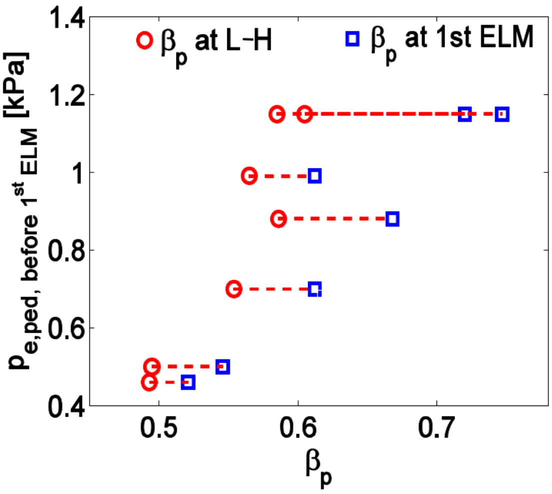

FIG. 6. Pedestal pressure height as a function of global β at both the time of the L-H transition and at the first ELM in MAST

4. Sustainment of pedestal improvements

Section 2.shows that by tailoring the evolution of the plasma discharge, an enhanced pedestal height can be achieved. This has been confirmed as the stabilisation of ballooning modes due to the increase in core pressure, explicated in section 3.However, for this method of pedestal improvement to be applicable in ITER, it is essential to demonstrate that the pedestal improvement can be sustained and that the ELM heat loads are tolerable.

In all machines the elevation of the critical pressure gradient for triggering ballooning modes means that the ELM period increases. In MAST, this longer time between ELMs means that the carbon impurity level increases in the pedestal region, diluting the ion density and increasing the pedestal temperature yet further. This leads to a self-perpetuating feedback which causes the global β to increase to the extent that Neoclassical tearing modes are triggered, ultimately degrading the stored energy and negating the improvement in the pedestal. Conversely, in JET the longer ELM periods result in an accumulation of tungsten in the pedestal region due to the absence of impurity flushing provided by the ELMs, which increases the radiated power and cools the pedestal again. However, we have shown that it is possible to optimise the stabilisation of ballooning modes such that the ELM period permits an improvement in pedestal height which can be sustained.

Figure 7 demonstrates that by increasing the core pressure, the pedestal can be improved, leading to a markedly increased global stored energy over multiple ELM cycles. This comparison shows two ostensibly identical plasmas, with the same shape, heating and engineering parameters. However, by tailoring the plasma evolution to increase the core pressure in the prelude to H-mode access, the pedestal height increases by $\approx 50\%$ with commensurate increase in stored energy. Eventually, even in TCV the β_N rises so much that tearing modes appear with a resul-

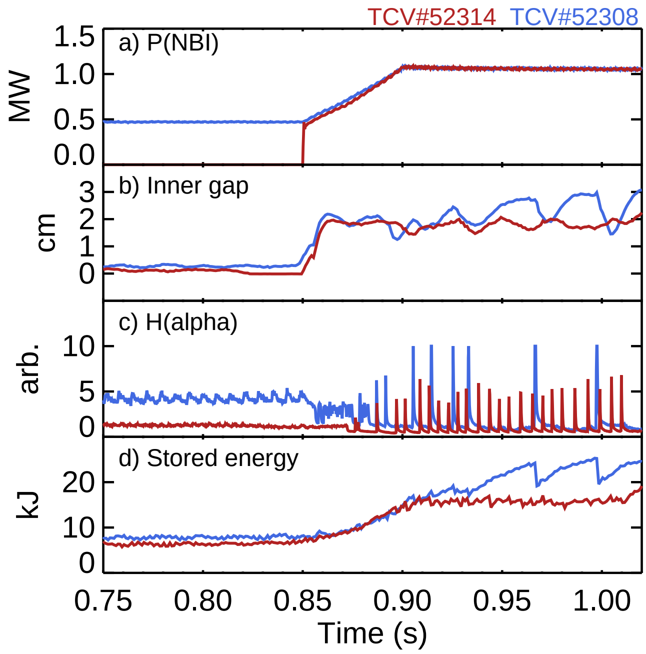

FIG. 7. (a) The NBI power, (b) the inner gap, (c) the H_α emission and (d) the stored energy in two TCV discharges. The heating in L-mode causes a larger core pressure (blue) resulting in less frequent ELMs and higher stored energy than the "normal" H-mode (red), with the enhanced stored energy sustained for multiple ELM cycles.

tant loss of confinement. We expect that core profile control and MHD control would enable this to be avoided, though this has yet to be demonstrated to be stable for many energy confinement times. Ultimately it is necessary to demonstrate that these benefits can be sustained in ITER-relevant scenarios for many energy confinement times with appropriate divertor conditions. In ITER it will be necessary to simultaneously protect the divertor, apply ELM pacing or suppression techniques and achieve a pedestal commensurate with $Q = 10$ performance.

5. Predictions of ITER pedestals achievable with evolution tailoring

The joint experiments in JET, MAST and TCV demonstrate that over a range of machine conditions, the pedestal height can be increased by appropriate tailoring of plasma evolution without requiring auxiliary systems otherwise used to effect such an improvement – such as additional heating, current drive systems, decreasing collisionality or increasing plasma shaping – none of which will be possible in ITER. In order to explore the possible benefits of this effect for optimising ITER performance, we have performed self-consistent integrated modelling to predict the pedestal performance in ITER given different initial conditions for the core plasma pressure.

We conducted a series of ITER baseline (B_T=5.3T, I_p=15MA, $n_{e,ped} = 7.5 \times 10^{19}\mathrm{m}^{-3}$, Z_{eff}=1.5) EPED simulations combined self-consistently with the core transport simulation using the GLF23 model in the JETTO code. The EPED predicted pedestal was used as the boundary condition in JETTO and the JETTO predicted core was used in the EPED. The loop was continued until the result converged. The prediction loops were started at different initial values of global β_N in an effort to simulate the fortuitous feedback mechanisms that are present in the plasma leading to the non-unique solution of the prediction. The high pedestal with stiff transport leads to high fusion power and high global β_N, which in turn increases the predicted pedestal height. On the other hand, the lower initial pedestal leads to low fusion power and low global β_N,

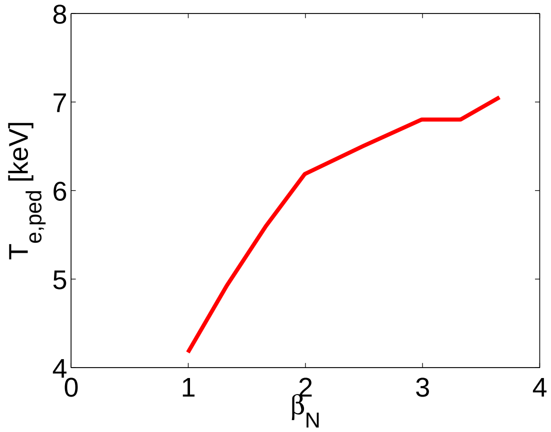

FIG. 8. Predicted ITER baseline pedestal temperature as a function of global β_N

and consequently prediction of a low maximum achievable pedestal. Figure 8 shows the dependence of the pedestal temperature of the global β_N. As can be seen, with $\beta_N \in [1,2]$, the pedestal temperature increases strongly with β_N, but beyond that the pedestal temperature increase is more modest. This is similar to results for JET [7, 11] and ASDEX Upgrade [12].

6. Summary

The pedestal height can be increased by tailoring the evolution of the plasma to provide a higher core pressure at the point of accessing H-mode. A higher core pressure in L-mode has been achieved in JET, MAST and TCV by suppressing H-mode access through small changes in the magnetic geometry. The enhanced core pressure stabilises the ballooning modes due to the combined effects from the increase in Shafranov shift and ellipticity. Since the critical pressure gradient to trigger peeling-ballooning modes increases, both the maximum achievable pedestal height upon H-mode access and the ELM period increase. In TCV it has been demonstrated that it is possible to sustain this enhanced performance for multiple ELM cycles. This method could be important for ITER, where the constraints placed by the metal wall could make operating with target pedestal for achieving $Q = 10$ difficult to achieve; by tailoring the plasma evolution improved pedestals may be attainable without requiring ancillary means unavailable to ITER that are also known to increase pedestal height, such as additional heating power. There remain open questions concerning the applicability of this method to ITER, notably the method for suppressing H-mode access since varying magnetic geometry is more constrained and whether the enhanced pedestal is compatible with ELM control and impurity control. Should these issues be resolved, predictive integrated modelling suggests that the pedestal height in ITER can be raised significantly by using evolution tailoring.

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