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The Influence of the Plasma Edge on the Performance of Tokamaks

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Abstract

The plasma edge region has a profound effect on the performance and operation of a tokamak. In this paper we describe some of the experimental and theoretical evidence for this assertion, emphasising H-mode confinement issues, such as the conditions for the L-H transition and the role of the H-mode pedestal, edge localised modes (ELMs) and the scrape-off layer.

Keywords:

tokamak, edge region, H-mode, ELMs, scrape-off layer

1. Introduction

The edge of the tokamak comprises the outer parts of the plasma column and the divertor or scrape-off layer (SOL) plasmas, which are strongly coupled together. This region can have a profound influence on a tokamak's performance. Firstly, the capability of the tokamak to produce a burning plasma depends on the value of the triple product $n\ T_i\tau_E$. Two of these factors, the density, n, and the energy confinement time, τ_E, can be strongly affected by edge phenomena. The density is often limited to the so-called Greenwald value, probably by atomic processes such as radiation near the plasma periphery, while τ_E is enhanced if the H-mode is accessed. The H-mode involves an edge transport barrier which can increase the ion temperature, T_i, and the sudden transition to H-mode from the L-mode clearly depends on edge phenomena. The improvement in confinement arises from both the 'pedestal energy', associated with the height of the edge transport barrier, and the apparent correlation of the core energy with the properties of this pedestal energy. Secondly, the H-mode is often associated with edge localised modes (ELMs). These degrade confinement by periodically depositing plasma into the SOL (the resulting transient heat loads appearing on the divertor target plates can pose a problem), but they are beneficial in controlling plasma density and impurity levels. Thirdly, the economic viability of a tokamak power plant is sensitive to the normalised plasma pressure β that can be sustained, and this can be affected by MHD instabilities occurring in the plasma edge region (these are also thought to be related to the onset of ELMs). Finally, the ability of the SOL to exhaust the steady power output of a burning plasma without excessive heat loads on the divertor plates depends on the width of the SOL; this problem can be alleviated or overcome by arranging for power to be radiated in the edge region or the plasma to be detached from the target plates as a result of atomic physics processes. We will review experimental evidence and theoretical ideas concerning these topics, emphasising the role of MHD stability.

2. The L-H Transition

The transition from L to H-mode can usually be characterised by a threshold heating power, P_{Th}, and empirical scaling laws for this in terms of global parameters have been obtained. However, the data displays much scatter, which leads to considerable uncertainties in P_{Th} when projecting to larger devices, and can exhibit a different behaviour at low n. Theoretical understanding of the transition in terms of local edge parameters might help reduce these uncertainties. Models fall into three broad categories [1]: (i) sudden suppression of turbulent transport by $\boldsymbol{E} \times \boldsymbol{B}$ flow shear, where the radial electric field E_r is determined by the ion radial pressure balance, (ii) stabilisation of modes when some critical value of a plasma parameter is exceeded, and (iii) neoclassical theories.

Flow shear stabilisation is an attractive universal paradigm: it leads to a variety of models depending on whether E_r is due to poloidal flow, V_θ, or ion pressure gradient, ∇p_i. In the first case the L-H transition appears as a bifurcation in the solutions to the equation for V_θ; this balances drives (*e.g*, due to ion-orbit-loss or Reynolds stress) against damping (*e.g*, due to neoclassical viscosity or charge exchange with neutral particles). The lack of clear experimental evidence for a dependence on collisionality argues against ion-orbit-loss, while there is experimental evidence for a role for Reynolds [2]. The low n behaviour of P_Th could be associated with charge exchange damping. However, while some devices see changes in V_θ preceding the transition, high resolution data from COMPASS-D and START indicates V_θ builds up afterwards [3]. Theories based on the ∇p_i contribution to E_r rely on a non-monotonic dependence of the fluxes on gradients due to flow shear. Most theories are 'local', ignoring the second order derivatives of p_i that contribute to ∇E_r, and allow a bifurcation in ∇p_i (including these undermines this attractive picture). Such theories lead to a critical value of the normalised ion Larmor radius, ρ_*, consistent with much experimental data.

Theories involving turbulence suppression as some parameter varies include those based on drift-resistive ballooning mode simulations and quasilinear estimates of drift Alfvén turbulence: these both involve critical collisionality and β-like parameters, which show some correlations with experimental data [4]. A model based on the current driven peeling mode instability criterion [5] explains the behaviour on COMPASS-D, where P_Th increases sharply at low n. In this model, the H-mode occurs if the collisionality, ν_*, is sufficient to suppress the edge bootstrap current and the normalised ballooning presssure gradient parameter, α, is sufficient to provide magnetic well stabilisation of the Ohmic current drive; experimental evidence from COMPASS-D in terms of local edge parameters supports this theory.

Finally, we mention models based on neoclassical theory, where the dependence of P_Th on the ion-∇B drift direction is suggestive. The theory has been revisited, taking account of the steep gradients in the plasma periphery: fluxes which are non-monotonic as functions of the edge gradients arise, permitting a bifurcation [6].

3. H-Mode Pedestal

In H-mode, an edge transport barrier forms a 'pedestal' in the pressure profile and the associated plasma energy, W_ped, is a significant part of the total plasma energy, W_plasma. An estimate of its contribution follows from assuming that the height of the pedestal is limited by setting the pressure gradient at the high-n (n is the toroidal mode number) ballooning limit, $\alpha = \alpha_\mathrm{crit}$, and establishing a prescription for the width of the barrier, Δ_ped. More detailed analysis of coupled peeling-ballooning modes at the plasma edge, shows that the conventional ballooning theory must be modified somewhat. Indeed one can expect significant 'finite-n' stabilising corrections to α_crit ($\propto n^{-2/3}$) [5]. This will be particularly significant in steep edge gradients and for the important intermediate values of n and could explain why some experiments find α values in excess of the high-n limit. Calculations also show that the radial envelope of the ballooning mode is $\Delta \propto a/n^{2/3}$ [5].

To complete the prescription for W_ped, we need an estimate of Δ_ped. One could assume that ∇p_i reaches such a value that the associated $\boldsymbol{E} \times \boldsymbol{B}$ shear is sufficient to stabilise some instability. Thus models involving ion temperature gradient (ITG) driven turbulence typically predict $\Delta_\mathrm{ped}/a \propto \rho_*^\gamma$ ($1/2 < \gamma < 2/3$), whereas, to stabilise MHD ballooning modes, one finds $\Delta_\mathrm{ped}/a \propto \rho_*^{2/3}$. This latter estimate coincides with one based on the region where there is a Reynolds stress from edge drift waves with $k_\perp \rho_\mathrm{i} \sim 0(1)$, since they will have an inhomogeneous mode structure over a width $\Delta \propto a/n^{2/3}$ [5], as for the MHD modes discussed above. These estimates are consistent with deductions on JET, although recent evidence from isotope scans has suggested the possibilities that $\Delta \propto \rho_\mathrm{i}$ (similar to that on JT-60U) and $\Delta \propto \rho_\mathrm{fast}$, the fast particle Larmor radius [7].

There is also evidence (*eg*, from ASDEX-Upgrade [8]) that the core energy, W_core, is controlled by the pedestal values T_ped or β_ped, consistent with predictions from 'stiff' transport models (*e.g*, based on ITG turbulence), which exhibit strong transport once a marginally stable temperature gradient is passed. Such models predict fusion powers in a burning plasma which are very sensitive to T_ped. The representation of energy confinement scaling as a 'two-term' form based on separate W_{ped} and W_{core} contributions, may be more helpful than the conventional power law scaling [7].

4. ELMs

ELMs, periodic disturbances of the plasma periphery in H-mode, are believed to result from MHD activity. They can be classified into Types I and III [9]. Type I occur for heating powers $P \gg P_{\mathrm{Th}}$, have a frequency, f_{ELM}, which increases with P and deposit a signficant fraction (say ~ 5%) of plasma energy, δW, and particles, δN, into the SOL; they do not always exhibit magnetic precursors and occur when $\alpha \sim \alpha_{\mathrm{crit}}$, although they can 'sit' there, implying some additional trigger is required. These features suggest pressure driven ballooning modes are involved. On the other hand, Type III occur when $P \gtrsim P_{\mathrm{Th}}$, have f_{ELM} decreasing with P and remove much smaller values of δW (say ~ 1%) from the plasma edge; they occur when $\alpha < \alpha_{\mathrm{crit}}$ and generally do exhibit magnetic precursors (typically with $5 < n < 15$). These features are suggestive of a resistive MHD explanation for Type III ELMs: they disappear as the resistivity drops with increasing heating. However, we shall discuss an alternative description of both types in terms of peeling-ballooning modes later.

The presence of ELMs has a number of impacts on tokamak performance, some beneficial, others less so. On the one hand, the removal of particles from the edge helps control of plasma density and impurities. However, one consequence of this, certainly for Type I ELMs, is the appearance of damaging transient heat loads on the divertor target plates. Furthermore, τ_{E} degrades as f_{ELM} increases, a consequence of the fact that the pedestal pressure gradient fails to heat up to its limiting value during an ELM period; this feature is evident on JT-60U and JET. One therefore has to balance the large value of δW from Type I with the high values of f_{ELM} associated with Type III ELMs: Type III are to be preferred.

A number of models have been advanced to explain ELM behaviour [9]. Some, based on stability criteria for various modes, are of a 'conceptual' nature, while others provide actual dynamical models. In the former category are models based on ideal or resistive peeling or ballooning modes appearing in the plasma periphery, or even the SOL; alternatively tearing and, indeed, micro-tearing modes have been advanced. In the second category are models which are based on either simulations of the primitive MHD equations (*e.g*, resistive interchanges in the SOL) or solutions of paradigm zero-dimensional models coupling the evolution of gradients, shear flows and MHD and/or drift wave fluctuation levels, which on the one hand are moderated by the shear flows and, on the other, determine the transport level.

We focus here on an example of the first category, namely coupled peeling-ballooning modes [5], although that due to the M-mode catastrophe involving stochastic magnetic transport [10] exhibits a number of features observed in experiments: fast time scales, transport avalanches and scalings for f_{ELM} and δW. In the peeling-ballooning mode model, the Type I ELM cycle is seen as a result of the following sequence: with additional heating the plasma enters a regime in which the stabilising magnetic well, proportional to α, overcomes the instability drive due to Ohmic edge currents (for high ν_* this is possible since the bootstrap current drive then disappears, as discussed in the L-H model for COMPASS-D in Section 2); it then heats up to the ballooning stability boundary where it sits, relatively benignly; with further heating the Ohmic and bootstrap currents increase until the peeling mode is triggered; the resulting loss of pressure gradient is further destabilising, leading to a catastrophic loss of pressure, and then the cycle repeats. The Type III cycle, relevant to cooler plasmas, can be understood as an earlier exit from the stable regime as diffusive processes build up the destabilising edge current density gradient faster than the stabilising edge pressure gradient. Stability calculations show that one can access a second stability regime in the presence of the peeling mode, provided there is a sufficiently deep magnetic well [5]. Such access could allow the pressure gradient to build up to such a level that when it eventually triggers some instability, a very damaging ELM-like event results; plasma shaping may help to prevent this.

5. Scrape-off Layer and Exhaust

Phenomena in the plasma periphery, and the SOL in particular, control the exhaust of plasma particles and energy. In the presence of ELMs and with sufficient pumping capacity, particle and impurity content appears controllable; the transient heat loads from ELMs point to the need to operate with Type III ones, as discussed in Section 4. That leaves the issue of the steady state power loadings on divertor target plates. The heat load intensity depends on the total incident power, P_{net}, and the width on the target plates, Δ_{SOL}, the heat is spread over. P_{net} can be reduced by either introducing seed impurities in a radiating edge layer of the core plasma, or arranging for a cold radiating region in the divertor chamber to allow detachment of the divertor plasma from the target plates.

We do not discuss this further here, but concentrate on what controls Δ_{SOL}. Balancing transport processes parallel and perpendicular to the magnetic field, characterised by diffusion coefficients $\chi_{\parallel}$ and $\chi_{\perp}$, respectively, one estimates $\Delta_{SOL} \sim (\chi_{\perp}/\chi_{\parallel})^{1/2} L_{\parallel}$ for a collisional SOL plasma (here $L_{\parallel}$ is the distance along the field line to the divertor plates); thus it depends crucially on $\chi_{\perp}$, which is often chosen simplistically in, otherwise, complex edge modelling codes. However, a substantial number of models for $\chi_{\perp}$ have been proposed in the literature. A comparison of the resulting predictions for Δ_{SOL} with data from collisionless SOLs in COMPASS-D and collisional SOLs in Alcator C-MOD and JET has, remarkably, shown that the same subset of models consistently provides the 'best-fits' [11]. These 'best' models invoke electromagnetic processes connected with the collisionless and collisional skin-depths or charge exchange processes involving neutral particles. For a collisional SOL these lead to predictions for Δ_{SOL} which are independent of n or B so that, on dimensional grounds, $\Delta_{SOL}/a \propto (L_{\parallel}/P)^{\gamma}$ with, typically, $1/4 < \gamma < 1/2$. In a burning plasma this leads to very narrow SOL widths, emphasising the need for detachment.

6. Conclusions

The plasma periphery influences tokamak performance: it controls or affects H-mode access, H-mode confinement, properties of ELMs and plasma exhaust. While there are many candidate theories to explain these phenomena, MHD stability considerations appear to play a significant role.

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