IMPROVED CONFINEMENT, HIGH-β REGIMES AND EDGE BEHAVIOUR ON THE COMPASS-D TOKAMAK WITH HIGH POWER ECRH AND LHCD

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Abstract

COMPASS-D, due to its small size (R=0.56m, a=0.18m) and long pulse length (relative to field diffusion times), provides valuable data when establishing the underlying physics and scalings for H-mode thresholds, confinement, and ELM behaviour for devices of the scale of ITER. It is found that the H-mode threshold has a very different parametric behaviour than that observed on larger devices, and new edge data provides a possible explanation. An adaptable 60GHz ECRH system has allowed high power ECRH (1.8MW installed power) to be used over a wide range of plasma parameters from low collisionality high β to high density H-modes. This system injects neither particles nor momentum, and is thus representative of the situation on ITER. A 1.3GHz 400kW LHCD system has provided additional flexibility for long pulse operation and optimisation of high β discharges (e.g. to avoid disruptions).

1. H-MODE THRESHOLD

COMPASS-D is the smallest device with well-characterised H-mode plasmas in ITER-like plasma configurations (i.e. single null divertor, with elongation ~1.6). Data are available for both confinement in ELMy-H-mode regimes, and for the power required to produce and sustain H-mode. Recent increases in the toroidal field have allowed ECRH to be used at the fundamental resonance (typically a launch angle of ±10-20^{o} to the toroidal field is used, balanced to minimise current drive). H-modes can thus be produced both Ohmically and with additional heating [1], and sustained ELMy-H-modes have been used to generate confinement data for the ITER confinement databases. The scaling of the threshold power (P_{th}) is very much at variance with the conventional scalings for ITER. In particular P_{th} increases as n_e falls (at low n_e), and there is a threshold density below which it is not possible to enter H-mode with the available power (more than an order of magnitude above that expected using the scaling laws derived from larger tokamaks) - this has also been observed on some other tokamaks [2]. The data are illustrated in Fig. 1. The power plotted is the estimated absorbed ECRH power (corrected for dW_{dia}/dt; the radiated power fraction is small), as deduced from a combination of ray tracing with the BANDIT-3D code and analysis of the time-evolution of the stored plasma energy (from EFIT and a fast diamagnetic loop) as the ECRH power is turned on or off. For heating at the fundamental the deduced absorption falls from about 80% to about 30%, as the density is increased from $1 \rightarrow 5\text{x}10^{19}\text{m}^{-3}$, due to refraction and variation in the optical depth.

The data are shown in terms of power delivered to the plasma, but it is expected that entry into H-mode is set by local parameters near the plasma edge. Earlier work on COMPASS-D in Ohmic H-modes had indicated that $\beta_n \equiv \beta_t/(I_p/aB_T)$ was a key parameter [3], with β_n being approximately the same for the H-L back transition as for the L-H transition. COMPASS-D global confinement in L-mode follows normal L-mode scaling, and therefore it is possible to calculate the power required to achieve a particular value of β_n in L-mode. If ITERL96th scaling is used, then the threshold power scales as

$$P_{th} \quad \beta_{n,crit}^{3.70} n_e^{-1.48} B_T^{3.59} A_i^{-0.74} R^{-3.30} a^{3.93} \kappa^{1.33} I_p^{0.15}.$$

This shows a strong inverse density dependence, very much as observed on COMPASS-D, and in addition a stronger toroidal field dependence than generally observed on other devices, but which helps to explain the noticeable difference between the $2\omega_{ce}$ 1.1T and $1\omega_{ce}$ 1.8T and 2.1T data on COMPASS-D. There is also an isotope scaling consistent with the observed lower threshold seen in deuterium as opposed to hydrogen-dominated plasmas. This scaling is plotted in

Fig. 1 for $\beta_{n,crit}$=0.53. For this to correspond with an edge parameter threshold, one has to make an assumption of profile similarity (i.e. that the edge pressure gradient is proportional to β_n as the density is varied).

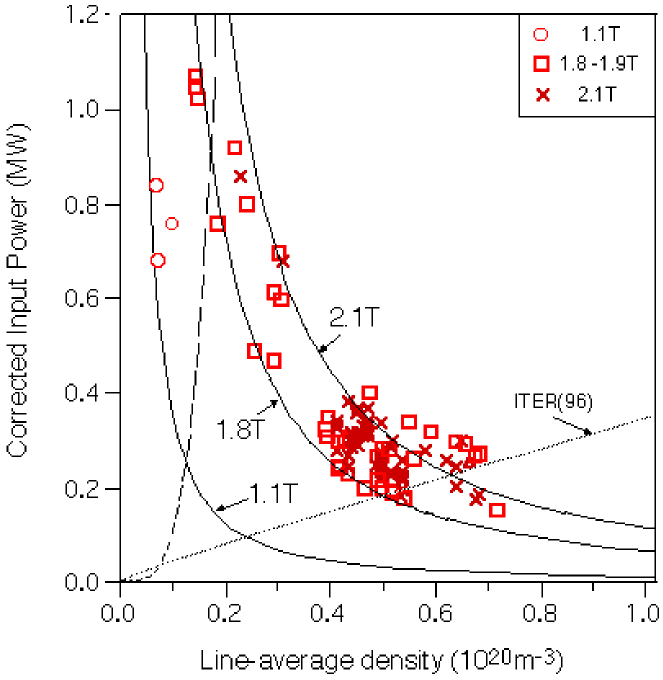

FIG. 1: Loss power (P_{abs}-dW/dt) at the transition to H-mode, as a function of line-averaged plasma density on COMPASS-D. Curves showing the power required for a critical average β_n using ITERL96th scaling are overlaid. The ITER(96) threshold scaling is also shown for B_T=2.1T [4]. The dashed line illustrates the form of the low density cut-off if due to a critical value of the collisionality.

Earlier observations that reducing the edge current by current ramp-down stabilises ELMs [5], together with the extremely high power required to enter H-mode in low density high beta plasmas, point towards the H-mode in COMPASS-D being related to stabilisation of instabilities driven by edge currents. The peeling mode is one such instability. This is a localised ideal-MHD instability resonant just outside the last closed flux surface, destabilised by edge currents and stabilised by pressure gradients [6]. At low collisionality it may not be possible to stabilise the mode at all, due to the edge bootstrap current. Using L-mode confinement scaling for a critical collisionality gives $P_{th}\quad n_e^{4.07}\nu_{*e,crit}^{-1.89}$ implying a sharp density cut-off, which for $\nu_{*e,crit}$~1 at the edge is close to that observed (~1-2x10^{19}m^{-3}, for B_T=1.1-2.1T). Furthermore, if the density is decreased while the plasma is in an ECRH H-mode, then an H→L back transition can occur.

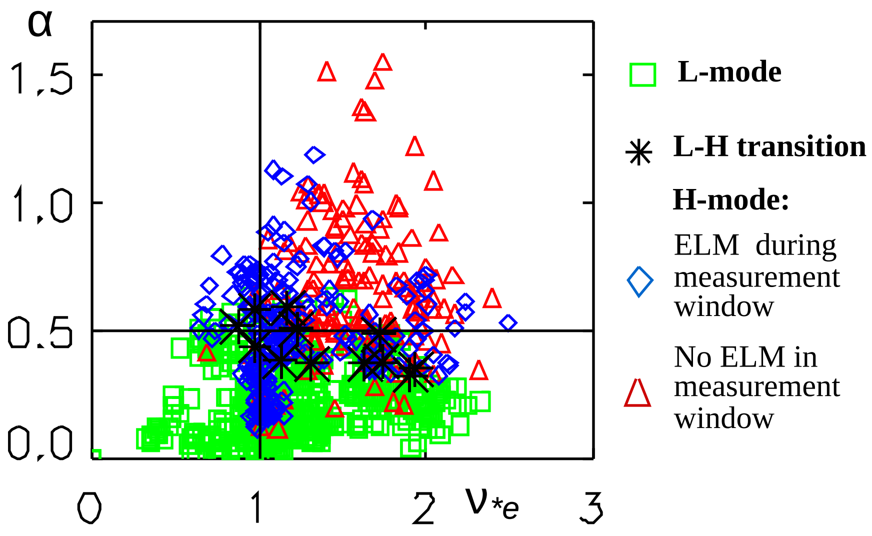

Fig. 2 HELIOS data from COMPASS-D showing that the normalised pressure gradient (α) and collisionality measured at the 90% flux surface reside in the peeling mode stable region (upper right hand sector) in H-mode.

A more precise test of the threshold for the peeling mode is now possible due to the recent installation on COMPASS-D of HELIOS, a diagnostic used to measure the edge n_e and T_e from spectral line intensities of a thermal helium beam [7]. Since the plasma power balance is dominated by electrons in ECRH H-modes, the collisionality and normalised edge pressure gradient (α) can be estimated. The COMPASS-D data (Fig. 2) are consistent with the peeling mode being stabilised in the discharges that make the transition into H-mode, with the ELM frequency decreasing as (α, ν_{*e}) change in the stabilising direction (it is not possible to define the stability boundary precisely with the data and model available). Whether peeling modes are indeed solely responsible for the edge turbulence seen in L-mode, or are manifest as the ELM precursors observed [8, 9], is not certain, but the peeling mode could destabilise other modes.

There are, however, many other mechanisms for the transition to H-mode, which may play a contributory even if not the dominant role. It is estimated that resistive ballooning mode turbulence [10] should be weak on COMPASS-D. There have been observations of changes in the poloidal and toroidal plasma flow on entry into H-mode, in the direction to generate radial electric fields which could reduce the turbulent transport, and with the flow changes being reversed by ELMs [11]. However the changes occur simultaneously with or after the transition or ELM (the data resolution is ~150μs), so that while they may assist the formation of the thermal barrier, it seems they do not initiate the transition. H-modes have not been generated with the ion grad-B drift away from the single null x-point in COMPASS-D, so ion loss effects cannot be ruled out, but there are no fast beam ions on COMPASS-D and no sharp change in the edge ion temperature is observed on transition [12]. One feature of the COMPASS-D data is not explained simply by the above peeling mode discussion: the *increase* in threshold power with density at higher densities. This data comes from Ohmic H-modes, however, and the threshold seems to be controlled almost entirely by the plasma density (the power does not change), perhaps again linked to a collisionality threshold.

2. LONG PULSE OPERATION AT HIGH PRESSURES

Early experiments [13] indicated that the current profile was important in the attainable β_n on COMPASS-D, with counter current drive (expected to raise $q(0)$) leading to higher β_n. The high β_n was transient, being limited by $m=2$, $n=1$ neoclassical tearing modes [14]. More recently experiments with $2\omega_{ce}$ ECRH injected early in the discharge at the start of the current flat-top [15] have led to sustained high β_n as measured by the diamagnetic loop (including fast electrons).

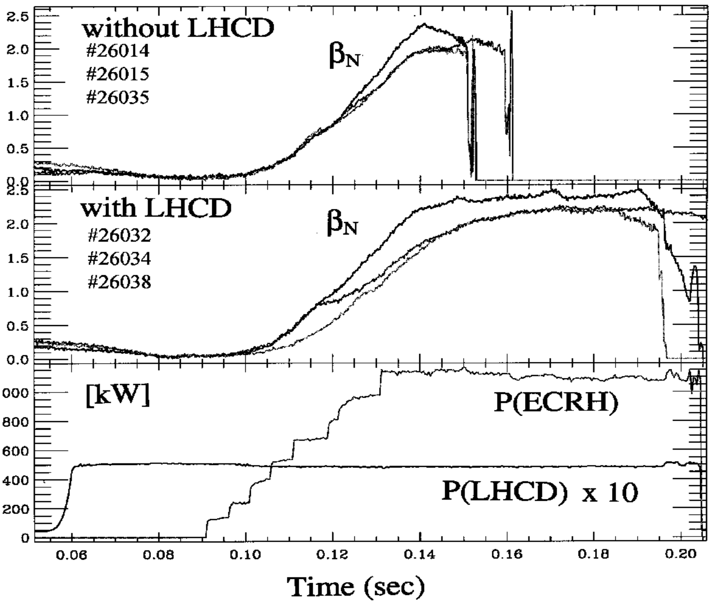

FIG. 3: Improvement in plasma stability and pulse duration by low power (50kW) LHCD added to an ECRH-dominated discharge (~1MW injected). Note the delay or avoidance of plasma disruption. $B_T=1.1T$, $I_p=155kA$, $<n_e>=0.8x10^{19}m^{-3}$.

It is found that even without full optimisation of the programming of the ECRH waveform, sustained high β_n can be achieved by using the 1.3GHz lower hybrid current drive system on COMPASS-D. Very modest LHCD power (50kW, $N_{//}=2.1$ oriented for co-current drive) added to ~1MW of ECRH, has led to stable 400ms pulses with β_n above 1.5 for ~200ms. As well as surviving longer, these discharges have lower levels of MHD activity, and the fast reconnection events are weaker. In these discharges, following the reconnection events, the MHD activity is reduced and the energy confinement shows marked improvement (~20%) over normal high-β plasmas. Ray-tracing calculations with the BANDIT-3D code, show that the current is driven in the outer part of the plasma (r/a>0.75) [16]. When applied to lower q plasmas that normally disrupt due to $m=2$, $n=1$ modes, disruptions are avoided or delayed (Fig. 3). These plasmas have V_{loop}≤100mV for timescales equivalent, compared to the resistive diffusion time, to ~20% of the ITER 1000s flat-top, at least comparable to much larger tokamaks. There is evidence both from modelling with ASTRA [17] (including bootstrap current ~50%I_p), and from the observed instabilities ($m=3$, $n=1,2$ dominant), that either $q(0)$ is high, possibly in excess of 2 in the optimised discharges, or that the profile is more stable to 2,1 modes. The pressure appears to be limited not by continuous $m=2$ neoclassical tearing modes but by fast reconnections, perhaps associated with the transient appearance of $q=2$ or destabilisation of 2,1 mode [18].

3. CONCLUSIONS

There is now an explanation for the unusual increase of the H-mode power threshold at low density on COMPASS-D, in terms of a critical pressure combined with L-mode confinement. This behaviour, together with minimum density for H-mode access and new data on the edge collisionality and pressure gradient, is consistent with peeling mode stability being a necessary and possibly sufficient condition for H-mode access at low density on COMPASS-D. This then justifies study of other possible roles of peeling modes in larger tokamaks, for example as a cause of ELMs [6]. Other mechanisms such as ion losses and velocity changes seem to be subordinate in initiating the L-H transition on COMPASS-D, but may assist the formation of a thermal barrier.

Careful optimisation of the programming of high power ECRH, and the application of off-axis current drive with LHCD, have led to a new high confinement regime with high β_n sustained for many confinement times, and up to ~20% of the duration (compared to the resistive diffusion time) needed for ITER, but without the large $m=2$, $n=1$ neoclassical tearing modes that limited earlier experiments on COMPASS-D.

Acknowledgements

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