

H-MODES ON COMPASS-D WITH HIGH POWER ECRH

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1. Introduction

The access to improved confinement (H-mode) is an important issue for ITER. COMPASS-D plasmas are of similar shape (single null divertor) to ITER, but are much smaller - at the lower extreme of the databases and hence extend the testing of models. Electron cyclotron resonance heating (60GHz) is used, which injects neither momentum nor particles (in contrast to neutral beam heating which is prevalent in databases) like alpha particle heating and the proposed RF schemes for ITER. Rotation/rotational shear is generally thought to be important for H-mode transitions. With $2\omega_{ce}$ ECRH, H-mode discharges are restricted to low density ($n_e^{cut-off} \sim 2.2 \times 10^{19} \text{ m}^{-3}$). Operation at higher toroidal field using fundamental ECRH high-field-side launch X-mode, ($n_e^{cut-off} \sim 8.9 \times 10^{19} \text{ m}^{-3}$) has considerably extended the density range, and higher triangularity ($\delta \sim 0.37$) discharges have been developed, at plasma currents up to 250kA.

With both central (2.1T) and off-axis heating (lower field) the power threshold shows a marked increase as the operating density is decreased [1] (Fig. 1), in sharp contrast to ITER scalings. This behaviour is seen over the whole of the ECRH operating regime; at the highest densities Ohmic H-mode develops. ECRH absorption is estimated from ray tracing and plasma energy dynamics. However since single pass absorption is computed to increase as the electron density is decreased, this is unlikely to be the cause of the threshold behaviour. In addition, confinement in ECRH (ω_{ce}) ELMy H-mode discharges on COMPASS-D, based on the assumption of complete absorption, lies typically within 50-80% of ITERH97-P and 0.85xITER93H, precluding large RF losses [2].

Theoretical calculations show that the peeling mode can be unstable at low densities because of increased edge bootstrap current [3]. This edge-localised MHD instability may prevent formation of an edge transport barrier, and hence H-mode, providing a possible explanation for the COMPASS-D results. An alternative explanation is provided by assuming profile resilience combined with confinement scaling, leading to a power threshold which increases as the density decreases. We discuss these ideas with reference to newly available boundary plasma data.

2. Experiments

Figure 1 shows the corrected input power ($P_{RF} + P_{OH} - dW/dt$) required to achieve H-mode, for ECRH (ω_{ce}) discharges with both on- and off-axis resonance, $150\text{kA} < I_p < 250\text{kA}$. Marked departure from ITER scaling (shown for 2.1T) is seen for deuterium plasmas. The power threshold is in general lower for off-axis resonance, corresponding to lower field, and is significantly higher for hydrogen discharges (deuterium operation is the norm on COMPASS-D). Total radiated power is estimated to be less than 30% at the L-H transition, increasing with operating density, and hence plays no significant role in determining the density scaling.

Triangularity also has no significant influence on the observed scaling. We first consider the absorption of ECRH power. Single-pass absorption is calculated by BANDIT-3D, a Fokker-Planck code which follows ray trajectories in toroidal geometry. Figure 2 shows computed single pass absorption for X-mode, high-field-side launch, corresponding to the COMPASS-D antenna configuration, as a function of line-average density, for parabolic density and temperature profiles.

Experimental estimates of total power absorption, from the rate of decay of plasma energy at the instant of fast termination ($\leq 20 \mu\text{s}$) of ECRH, are broadly consistent with the trend shown in Fig. 2. There is no evidence therefore of a large decrease in ECRH absorption at low density, which might have explained the observed scaling with density.

Plasma boundary diagnostics on COMPASS-D have recently been improved with the installation of HELIOS [5] (helium injection and optical spectrometry) which provides edge electron density and temperature profiles up to $\sim 2\text{cm}$ inboard of the separatrix. Figure 3 shows data from an ECRH H-mode discharge (values at the 90% and 95% poloidal flux surfaces) where changes in gradients inboard of the separatrix are seen at the time of the L-H transition, and further changes occur during the subsequent ELM-free period. Such

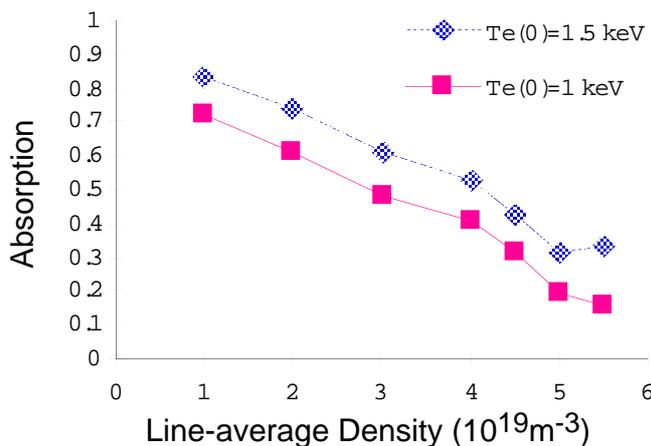


Fig. 2. Single pass ECRH(ω_{ce}) absorption in COMPASS-D (X-polarisation, high-field launch) calculated from BANDIT-3D, for two assumed central electron temperatures, parabolic density and temperature profiles, $B_T = 2.1T$.

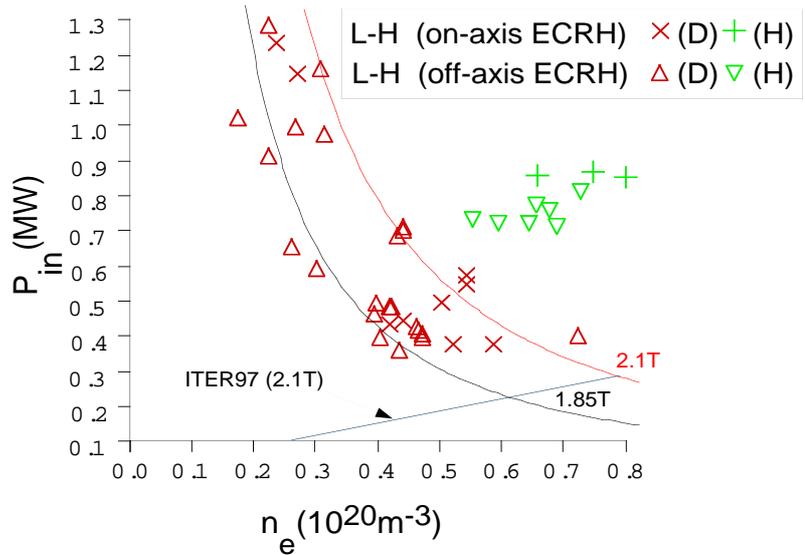


Fig. 1. Power threshold in ECRH (ω_{ce}) COMPASS-D discharges. The lines through the deuterium data correspond to scaling derived from confinement (τ_E^{96LH}) and a β_N threshold: $P_{\text{thresh}} \sim B_T^{3.7} n^{-1.5}$. ITER97 scaling [4]: $P_{\text{thresh}} = 0.65 n_e^{0.93} B_T^{0.86} R^{2.15}$

measurements are now available for limited regions of the discharge parameter range of Fig. 1. Poloidal and toroidal plasma flow velocities, and impurity ion temperatures near the plasma edge are provided by high resolution Doppler impurity spectroscopy.

3. Discussion

We discuss whether the L-H threshold behaviour on COMPASS-D is consistent with the requirement of peeling stability for achieving H-mode. The peeling mode is an edge MHD instability driven by current density and stabilised by pressure gradient. A

criterion for stability is $\sqrt{1-4D_M} > 1+\gamma j_{\parallel}/SI_p$ where D_M is the Mercier criterion for localised pressure-driven modes, S is the shear, j_{\parallel} is the total edge current density and γ is a constant. Separating out the effect of the bootstrap current, a schematic representation of stability is $\alpha(\epsilon-f/\epsilon) > j_{\parallel}^{\text{OH}}$ [3], where α is the local normalised pressure gradient (ballooning parameter) and $j_{\parallel}^{\text{OH}}$ the Ohmically driven edge current density. f_t , the trapped electron fraction, is reduced by increasing collisionality ν^* . If ν^* exceeds ν_{crit}^* (~ 1) then the peeling mode is stable above some critical pressure gradient, α_{crit} . For collisionalities $< \nu_{\text{crit}}^*$ the mode is unstable for all α . Figure 4a shows a plot of experimentally determined ν_e^{*90} vs n_e^{90} (values on 90% poloidal flux surface) at L-H transitions, together with data from discharges where H-mode could not be achieved. L-mode

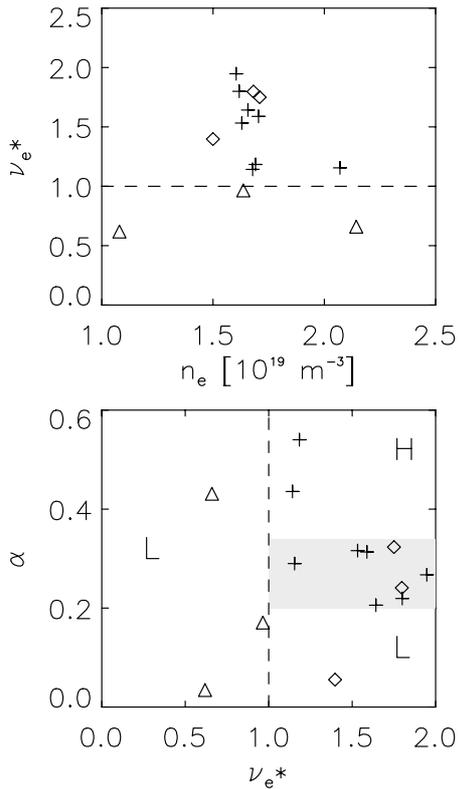


Fig. 4a. ν_e^{*90} vs. n_e^{90} values at L-H transitions (crosses), together with L-mode data (open points)

Fig. 4b. Corresponding α^{90} vs. ν_e^{90} values, mapping out boundary of H-mode operating regime. Boundaries will be broadened by experimental uncertainties etc.

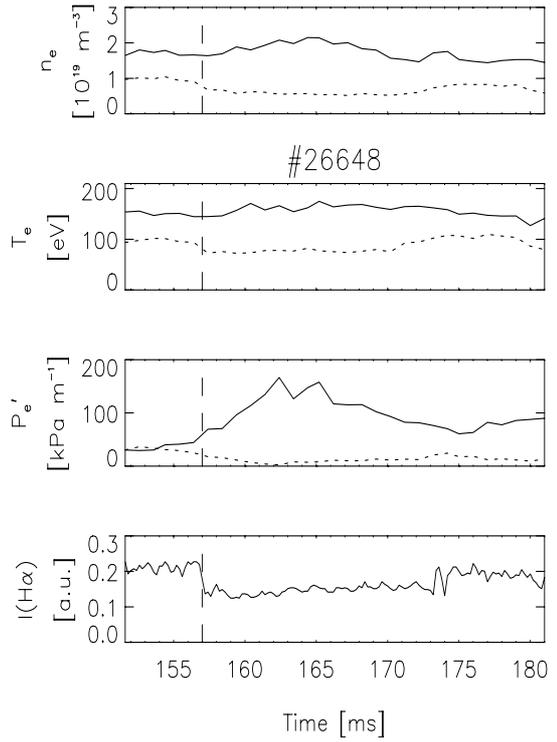


Fig. 3. Edge electron density, temperature, electron pressure gradient and $D\alpha$ time histories COMPASS-D ECRH H-mode discharge. Measurements are shown at the 90% (full) and 95%(dashed) poloidal flux surfaces. Vertical dashed lines indicate the L-H transition.

points (triangles) below the $\nu_{\text{crit}}^* \sim 1$ line can be regarded as intrinsically peeling mode unstable, those above the line (diamonds) are unstable if $\alpha < \alpha_{\text{crit}}$. Figure 4b plots α against ν^* for the same discharges, the L-H transition points mapping out quite clearly the boundary to the H-mode operating regime, L-mode points at higher collisionality lying on or below α_{crit} . Experimental errors on the data will partly obscure these boundaries. Additional deviation from a sharply defined α_{crit} may arise since changes in $j_{\parallel}^{\text{OH}}$ are expected to lag behind those in α , due to current diffusion timescales. Note also that the L-mode points are those for maximum power input, (maximum α) which might be expected to lie close to the boundary.

In terms of global observations (Figure 1), if the local temperature and density are proportional to global average values, and applying L-mode confinement scaling ($\nu^* \propto n/T^2 \propto n^3/(P\tau)^2, \tau = \text{ITER96Lth} \propto P^{-0.73} n^{0.4} A^{0.2}$) contours of constant ν^* correspond to $P \propto n_e^4$. On a linear-scale graph of P

vs. n_e , such as Figure 1, the v_{crit}^* contour will appear essentially as a vertical line, or density threshold. It is significant that ECRH H-mode discharges on COMPASS-D close to threshold appear to be dominated by density behaviour - at constant heating power L-H and H-L transitions can be triggered by minor (few %) variations in density (see Figure 5), consistent with crossing such a density threshold. In terms of additional stability requirements, a critical value for α can be interpreted as a threshold in normalised plasma pressure β_N , again assuming profile resilience. The power required to attain a given β_N ($\beta_N \propto P\tau/BI_p$) results in the scaling $P_{\text{thresh}} \propto n^{-1.5} B^{3.6} A^{-0.75}$ which is a good match to the data (Figure 1), and furthermore predicts the increased threshold seen in hydrogen. Many other devices report a low density threshold. In particular TdeV, also heated by ECRH, observe a sharp increase in power threshold at low density [6].

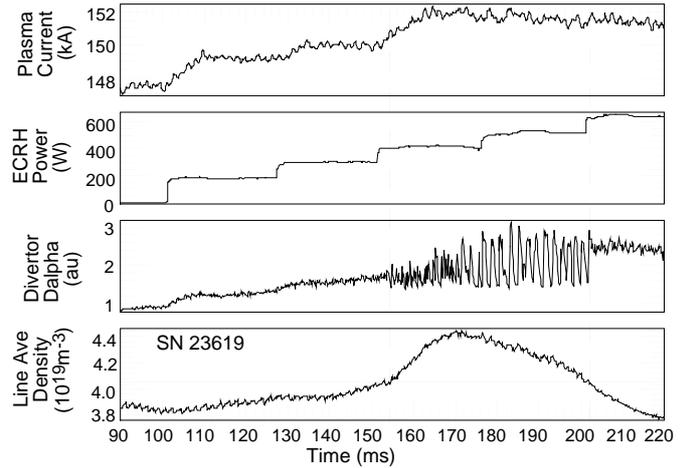


Fig. 5. COMPASS-D ECRH discharge showing L-H and H-L transitions occurring at the same density, despite increase in ECRH power. The transitions (dashed line) appear to be driven predominantly by density behaviour.

We conclude therefore that L-H transition behaviour on COMPASS-D at low densities is consistent with a transition controlled by stabilising the peeling mode as a necessary, but possibly not sufficient, criterion. At the highest densities, the COMPASS-D ECRH H-mode power threshold no longer decreases as density increases, indicating that some other mechanism may be determining the behaviour. We suggest that peeling mode stability is a necessary requirement for H-mode. It may not however be the controlling mechanism in all regimes on COMPASS-D, or on other devices with different heating schemes and plasma regimes (e.g. the ratio of pressure to current diffusion times is likely to play a role). It may not be a coincidence that the strong link between the L-H transition and sheared flows is only observed on tokamaks with auxiliary heating which provides significant momentum to the plasma. On COMPASS-D significant plasma rotation changes are not detected prior to the L-H transition and in general develop only in ELM-free periods [7]. To test peeling mode stability further needs transport simulations to relate the power to local edge pressure and other measurements, as well as to investigate the competition between timescales associated with pressure and current diffusion.

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