

Energy Confinement of ELMy H-mode Plasmas on COMPASS-D Tokamak with ECR Heating

M Valovič, S J Fielding, B Lloyd, S J Manhood, A W Morris,
T Pinfold, K Stammers, C D Warrick
and the COMPASS-D and ECRH Teams

*EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxfordshire
OX14 3DB, U.K.*

Introduction

ELMy H-mode is a reference regime for next step devices such as ITER. Recent reductions in the size of this machine result in a shorter energy confinement time. This makes equipartition weaker leading to a noticeable difference between electron and ion temperatures ($T_e > T_i$). ELMy H-modes where heat is primarily deposited to electrons are rare so far.

COMPASS-D routinely operates in stationary ELMy H-mode with Electron Cyclotron Resonance Heating. These regimes also utilise a relevant high triangularity plasma shape. Such plasmas expand confinement databases towards low values of normalised Larmor radii where L-mode (Bohm) and H-mode (gyro-Bohm) energy confinement scalings predict interestingly very close values.

The present paper describes the conditions for the ELMy H-mode regime with ECRH and presents the energy confinement data for such plasmas. We also report how these plasmas can be used for dimensionless-scaling experiments. On COMPASS-D, a factor-of-five collisionality scaling is possible and the first results are reported.

Experimental conditions

A stationary ELMy H-mode regime on COMPASS-D, with on-axis ECRH, is observed albeit in a relatively restricted operational window. ECRH dominated ELMy H-mode has been produced so far only at fundamental resonance ($f_{ecrh}=60\text{GHz}$). In this regime the waves are launched from up to 5 high field side antennae with X-mode polarisation and oblique propagation relative to the major radius ($\pm 33^\circ$ at launch position). Launching angles are balanced, as far as possible, so that no significant current drive is expected. Deuterium, single null divertor plasmas ($a=0.17\text{m}$, $R=0.56\text{m}$, $\kappa=1.7$, $\delta=0.4$) are used in these experiments. The geometry is illustrated in Fig. 1.

The operational window for stationary ELMy H-mode is determined simultaneously by density and power thresholds. Line-average densities above $\bar{n}_e \sim 3.6 \times 10^{19} \text{m}^{-3}$ and launched power greater than $P_{ecrh} \sim 0.5 \text{MW}$ is required. The transition from L-mode to ELMy H-mode is typically gradual through a period of small high frequency ELMs. In order to achieve a regime with well-separated ELMs, plasma shape with increased triangularity seems necessary although no systematic comparisons were made. These regimes can last for the whole duration of the heating pulse as illustrated in Fig. 2.

In these experiments the maximum plasma current was $I_p=245\text{kA}$. With decreasing plasma current the ELM frequency decreases and at $I_p=150\text{kA}$ ELM-free H-mode is observed. At low plasma current, L-H transitions become sharp, no longer assisted by high frequency ELMs.

Confinement

Absorption of X-mode polarised waves at fundamental resonance has an inverse density dependence. Thus, with densities above the H-mode threshold the single pass absorption is not complete. The actual values depend on electron temperature. Fig. 3 shows the central electron temperature as measured by Thomson scattering. In sawtooth discharges, with central ECRH, there is a scatter in the electron temperature measurements and for better representation we have averaged over 3 measurement points inside $r/a<0.1$. It is seen that for ECRH ELMy H-mode plasmas the central electron temperature reaches $T_e(0)\approx 1.5\text{keV}$ in comparison with $T_e(0)\approx 0.9\text{keV}$ for Ohmically heated plasmas which remain in L-mode. It also shows that the central temperature is density independent. Fig. 4 shows the absorption calculated by ray-tracing (BANDIT-3D [1]) using model density and temperature profiles. The code calculates essentially the single pass absorption (at higher densities considerable refraction could also result in double-passes through the resonance layer). Part of the unabsorbed power reaches the upper hybrid resonance layer localised just inside the outboard edge of the plasma or part is refracted to the wall (Fig. 1). In both cases waves can be directed back to the resonance layer but the magnitude and distribution of this re-absorption is uncertain and is not included in the modelling.

Absorbed power was also estimated from the change of the time derivative of energy content at the power switch-off: $P_{abs} = -\lim_{\Delta t \rightarrow 0} [dW/dt]_{t_0-\Delta t}^{t_0+\Delta t}$. A practical difficulty with this method is to choose a Δt that is sufficiently smaller than the energy confinement time but on the other hand long enough so that the linear regression is a representative average of dW/dt over the ELMs. In our case $\Delta t=2\text{ms}$ was a good compromise and results are shown in Fig. 4. Values deduced from both diamagnetic and equilibrium (EFIT) energy contents are similar and close to the single-pass predictions by ray-tracing. There is however a fundamental uncertainty related to this method, namely the assumption that energy confinement time is a continuous function across the time when the auxiliary heating power is switched-off. A discontinuity may arise from the ‘‘profile stiffness’’ and we can not evaluate this uncertainty. In conclusion, we consider the range represented in Fig. 4 as a lower estimate for the absorbed ECRH power.

The energy content shows an approximately linear dependence on density in the range where ECRH ELMy H-mode is observed (Fig. 5). The variations of nominal ECRH power are small (Fig. 3) and are not related to density. In ECRH ELMy H-modes, Ohmic power systematically decreases with increasing density $P_{oh}=0.15\text{MW} \rightarrow 0.1\text{MW}$. This is in contrast to the density independent central temperatures (Fig. 3). Edge conditions, however, change significantly from high frequency ELMs at the L-H density threshold at $\bar{n}_e=3.6\times 10^{19}\text{m}^{-3}$ to regular large ELMs at $\bar{n}_e=5.1\times 10^{19}\text{m}^{-3}$. This may be related to higher edge electron temperature and hence lower Ohmic power as the density increases. Assuming 40% absorption at the maximum density the energy confinement is equivalent to $H_H=0.8$ relative to the ITERH98y ELMy H-mode scaling [2]. For the whole range of

densities, and for both Ohmic and ECRH heated plasmas, ITER scalings predict a small improvement across the L-H transition: $\tau_{E,ITERH}/\tau_{E,ITERL}=1.1-1.2$ [2].

Collisionality (ν^*) scan

Data from ECRH ELMy H-mode plasmas together with those from Ohmically heated ELMy H-mode plasmas can be used to test the collisionality dependence of the energy confinement. Table 1 shows parameters of such two shots. The shots differ by a factor of 5 in volume-averaged collisionality while differences in other dimensionless parameters are small. It is seen that the dimensionless thermal diffusivity $\chi^* \equiv \tau_{Bohm}/\tau_E$ increases only weakly with ν^* . Here, $\tau_{Bohm} \sim T/B_T$, where T is the volume-averaged temperature calculated from the energy content. The contribution of dW/dt to the energy confinement time τ_E is small. The match in q_{95} , normalised Larmor radius ρ^* and β is not exact due to both the proximity of the L-H threshold and the uncontrolled heating power in Ohmic plasmas. Thus, the exponent y_ν in the usual power law scaling $\chi^* \propto \rho_*^{y_\rho} \beta^{y_\beta} \nu_*^{y_\nu} q^{y_q}$ can not

Table 1.

	#26363 0.147s ECH	#27907 0.245s OH
q_{95}	4.6	4.3
B_T [T]	2.07	1.1
I_p [kA]	242	140
n_{19}	5.1	5.4
P [MW] _{40%abs}	0.34	0.18
W [kJ]	4.9	2.2
$T_e(0)$ [keV]	1.4	0.66
f_{ELM}/f_{ST} [Hz]	500/350	400/650
β_N	0.58	0.80
ν^* [a.u.]	4.5	24
ρ^* [a.u.]	9.6	12
χ^* [a.u.]	10	15

be calculated exactly but the range can be given using assumptions for the other exponents. From the ITER database $y_\rho=0.83\pm 0.27$, $y_\beta=0.50\pm 0.24$, $y_\nu=0.10\pm 0.08$ and $y_q=2.5\pm 0.49$ [2, 3]. Assuming these values for y_ρ , y_β and y_q the data from Table 1 give $y_\nu=0.14$. We have also conducted a sensitivity study by varying the exponents one-by-one around the above values in the indicated ranges and found the collisionality exponent in the range $y_\nu \in (0.08, 0.20)$. When the assumption on absorbed power is varied from 35% to 60% then y_ν changes from 0.19 to 0.

Conclusions

COMPASS-D routinely operates in stationary ELMy H-mode with ECRH in high triangularity SNX geometries. These plasmas provide valuable confinement data in the regime where heat is deposited primarily to the electrons. An intra-machine factor-of-five collisionality scan is demonstrated. Results show a weak-positive dependence of thermal diffusivity in agreement with the ITER database and single machine scans [4]. These plasmas may be used also for ρ^* -scan experiments in conjunction with larger tokamaks.

This work was jointly funded by the UK Department of Trade of Industry and Euratom. The DIII-D group at GA is acknowledged for providing the EFIT code and L C Appel for its installation.

- [1] M R O'Brien *et al*, Proc. IAEA Technical Committee Meeting on Advances in Simulation and Modelling of Thermonuclear Plasmas, Montreal (1992) 527
- [2] K Thomsen *et al*, 17th IAEA Fusion Energy Conference, Yokohama (1998)
IAEA-CN-69/ITER/3-ITERP1/07
- [3] M Valovič *et al*, 25th EPS Conference, Praha (1998) B122PR
- [4] C C Petty, Phys. Fluids, **6** (1999) 909

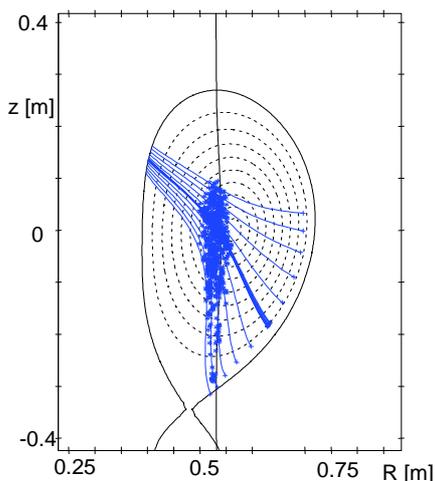


Figure 1. Plasma geometry and ECRH from ray-tracing (BANDIT-3D).

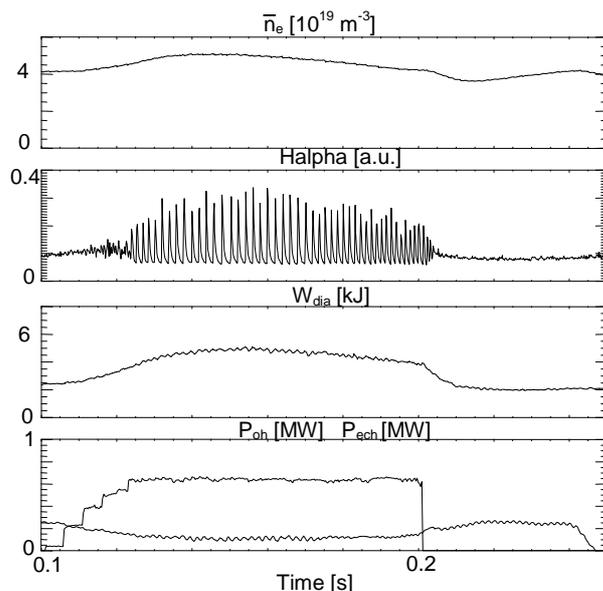


Figure 2. Stationary ELMy H-mode with ECR Heating. Shot 26363.

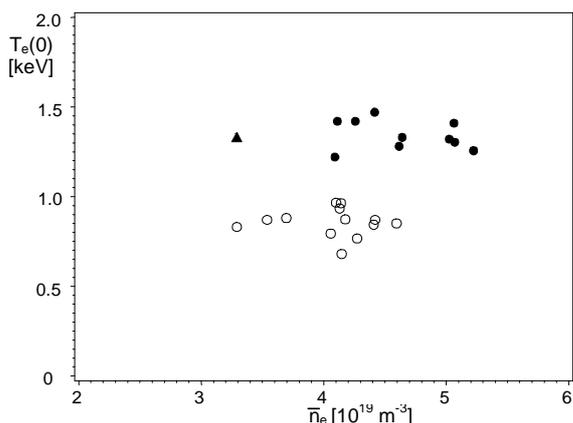


Figure 3. Central electron temperature at different line averaged densities for ECRH ELMy H-mode (full circles), ECRH L-mode (full triangles) and Ohmic L-mode mode (open circles) $P_{\text{launched}}=520-650\text{kW}$, $I_p=233-245\text{kA}$, $B_T=2.07\text{T}$.

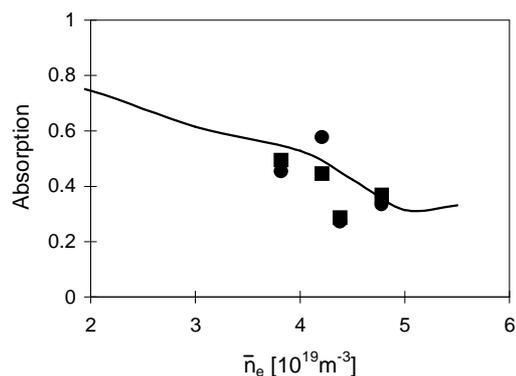


Figure 4. Calculated ECRH absorption for $T_e(0)=1.5\text{keV}$ (solid line) and values deduced from break-in-slope analysis (circles: dW_{dia}/dt , squares: dW_{mhd}/dt).

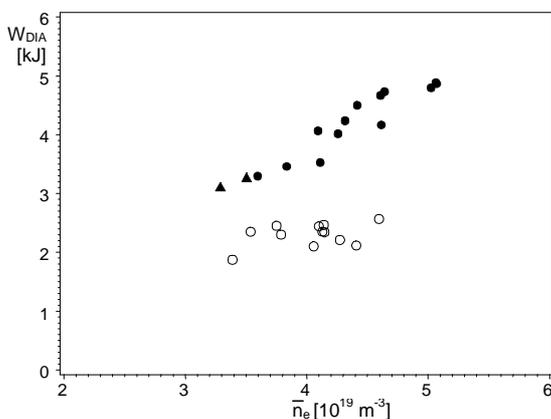


Figure 5. Energy content for ECRH ELMy H-mode (full circles), ECRH L-mode (full triangles) and Ohmic L-mode (open circles). Accuracy $\delta W \sim \pm 13\%$.