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THE CONFINEMENT AND STABILITY OF QUASI-STATIONARY HIGH β PLASMAS ON COMPASS-D

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Introduction

On COMPASS-D, the β limit can be degraded by the onset of (m=2,n=1) neo-classical tearing modes [1]. Active avoidance of these modes has been demonstrated by optimisation of the current ramp-up phase and careful adjustment of the ECRH timing, thus maintaining high β performance (β_N~2, β_p>1) with >1MW of ECRH power for an appreciable fraction of the current diffusion time [2]. The energy confinement of these plasmas is τ_E ~ 4-5ms which is higher (by a factor of ~2) than the ITER L-mode thermal scaling [3]. There are indications in some shots, especially with early ECRH heating, of improved core confinement [2]. In further experiments with unoptimised ECRH heating, the high performance phase was reproducibly curtailed by the appearance of a large (2,1) mode. This was *avoided* with modest levels of LHCD power (~50kW) applied prior to and maintained throughout the ECR heating pulse, ensuring a longer high performance phase with a higher achievable β [4].

In more recent experiments LHCD has been used to stabilise *pre-existing* neo-classical tearing modes in high β ECRH heated plasmas. LHCD at modest powers (60-70kW) has a strong stabilising effect on the (2,1) neo-classical tearing mode, reducing the mode amplitude to almost zero in some cases, with a subsequent rapid growth in amplitude after the LHCD pulse. The present paper is concerned with these recent stabilisation experiments.

Stabilisation of Neo-classical Tearing Modes with LHCD

These experiments were performed in single null divertor plasmas (I_p~140kA, B_ϕ=1.1T, q_{95}~ 3.7, κ=1.5) with up to 1MW of second harmonic 60GHz ECRH in the plasma core. The ECRH waves are launched from antennas on both the low and high field side of the tokamak with balanced injection angles to ensure no significant net EC current drive. These experiments were carried out at low line averaged electron densities ($0.6\text{-}0.8\times10^{19}/m^3$ maintained by feedback control), well below the second harmonic ECRH cut-off, to encourage the de-stabilisation of neo-classical tearing modes. ECRH avoids central fuelling or significant momentum input to the plasma, similar to the primary heating mechanism in a burning plasma device. The 1.3GHz LHCD system on COMPASS-D uses a conventional eight waveguide antenna with a phasing of 60° between adjacent waveguides (peak $N_\parallel$~2.1).

Almost all shots with high power ECRH were characterised by the natural growth of a (2,1) neo-classical tearing mode with the mode onset at β_p ~ 0.6-0.7. The application of a short 20ms LHCD pulse, after the mode had grown, clearly resulted in a reduction in the mode amplitude followed by an increase after the LHCD had been switched off (see Figure 1). The initial growth of the neo-classical island is seen to limit the rise in β before the LHCD is applied. A gentle roll-over in performance is then observed, partly caused by the temporary loss of one of the ECRH lines for a short period (5ms). As the LHCD power is ramped up and the ECRH recovers to full power, the performance recovers and the increase in β is sustained whilst the LHCD power (~75kW launched power in this case) is applied and the mode amplitude decreases. The mode amplitude is observed to decrease to almost zero during this phase, albeit transiently, and this is approximately correlated with the best performance (β_N ~ 1.7, β_p ~ 1.05). The mode amplitude recovers somewhat as the density increases and the LH driven current is reduced. A rapid increase in mode amplitude, back to the level observed before the LH was applied, is observed soon after the LHCD is turned off, coincident with a decrease in β. In a similar shot with less LHCD power (~55kW), the transient decrease in mode amplitude during LHCD is less pronounced (~30%), although an increase in mode amplitude after the LH is switched off is observed again. In this second case, the presence of the mode (albeit smaller) throughout the LHCD pulse restricts the β more significantly (β_p restricted to 0.95 during LHCD). The improvement in achievable β_p with improved mode stabilisation at increased LHCD power is limited by the short LHCD pulse. Higher performance (β_N > 2) is expected with longer, higher power LHCD pulses.

In separate experiments, the mode was deliberately seeded by the formation of a (2,1) island in the plasma using the highly adaptable error field saddle coil set on COMPASS-D. The β_p threshold for growth of the mode was observed to depend on the size of the seed island, consistent with neo-classical tearing mode predictions. The application of LHCD in these cases also showed a reduction in the neo-classical mode amplitude. For example, with ~65kW of LHCD power, the mode amplitude was observed to decrease by 40-50% and was characterised by a sharp increase after the LHCD was switched off.

The LH driven current profile has been estimated using the BANDIT-3D combined Fokker Planck and ray tracing code [5] together with electron temperature measurements from the Thomson scattering system. The bulk of the driven current is located in the outer region of the plasma (r/a~0.5-0.7) although a small amount of current is driven in the plasma core. Due to the low densities in these discharges, the driven current is ~60kA (~40% of the plasma current) after accounting for the directivity of the LH antenna (77%) and the reflected power (~30%). This is consistent with the observed drop in loop voltage.

MHD mode analysis

The (2,1) modes observed in these experiments are neo-classical in nature as they grow approximately linearly with the observed β_p. A comparison of the measured island width (associated with the mode) and the island width predicted from a solution of the modified Rutherford island evolution equation was undertaken.

The measured island width was determined from just before to just after the LHCD pulse for the shot shown in Figure 1, using the approximate cylindrical formula [1]:

$$w = 4r_s\left[\left(\frac{q}{m\varepsilon}\right)\left(\frac{L_q}{r_s}\right)\left(\frac{b}{r_s}\right)^{m+1}\sqrt{1+(\omega\tau_w)^2}\,\frac{\tilde{B}_r(b)}{B_\phi}\right]^{1/2}$$

where r_s is the radius of the q=2 rational surface, m is the toroidal mode number, ε is the inverse aspect ratio, L_q is the local gradient scale length of the safety factor, b is the effective radius of the vacuum vessel, ω is the mode frequency, τ_w is the effective resistive wall time (210μs on COMPASS-D) and $\tilde{B}r(b)$ is the perturbed radial magnetic field measured at the wall (by external saddle coils). The measured island width (see Figure 2), clearly shows a reduction during the LHCD pulse. It should be noted that this is only an estimate of the island size as accurate measurements of L_q and r_s were not available.

Also shown in Figure 2 is the island width calculated by solving the modified Rutherford equation which determines the neo-classical island growth rate [6]:

$$\frac{dw}{dt} = \left(\frac{1.22\eta_{nc}}{\mu_0}\right)\left[\Delta' + a_1\varepsilon^{1/2}\beta_p\left(\frac{w}{w^2+w_c{}^2}\right) - a_2\left(\frac{\rho_{\theta i}{}^2\beta_p g(\varepsilon)}{w^3}\right)\right]$$

where η_{nc} is the neo-classical resistivity and a_1 and a_2 are coefficients that depend on the details of the equilibrium. The first Δ' term represents the usual current gradient drive and the second term represents the neo-classical bootstrap current drive with w_c parameterising the contribution of the $\chi_{\perp}/\chi_{\parallel}$ stabilising term [7]. The third term represents the contribution from the ion polarisation current [8] where ρ_{θ_i} is the poloidal ion Larmor radius and g(ε) is a function dependent on the collisionality of the plasma. Using similar parameters to those used in determining the measured island width and restricting the unknown parameters ($r_s\Delta'$, a_1 and a_2) to reasonable values, an acceptable fit to the measured island width before the LHCD pulse can be obtained, further indicating that the mode is neoclassical in nature. As there is no evidence that the island width was saturated after the LHCD was turned off, good agreement between the measured and calculated island width is not expected at this time.

Theoretical studies have shown that localised heating and/or current drive in the island itself results in stabilisation of the neo-classical tearing mode [9] and experiments to study the effect of injecting modulated ECCD into a neo-classical island have been undertaken on ASDEX-Upgrade [10], with some success. Further theoretical studies [11] have suggested that the presence of a less localised DC driven current profile in the vicinity of the rational surface can also stabilise neo-classical tearing modes, decreasing the Δ' term with favourable current gradients inside and outside the rational surface. It is thought that this mechanism may be responsible for the mode stabilisation observed with LHCD on COMPASS-D. Further solutions of the Rutherford equation indicate a significant reduction in the island size (30-40%) during the LHCD phase with a modest decrease in the Δ' term of only a factor of ~2, roughly consistent with theory for the driven current predicted in these experiments.

Summary

Previous experiments on COMPASS-D have demonstrated the effectiveness of modest levels of LHCD for actively *avoiding* performance limiting (2,1) neo-classical modes in high β ECRH heated discharges. More recent experiments have shown a clear stabilisation of *pre-existing* modes with off-axis LH driven current. The island width, associated with the mode, has been estimated from measurements and compared to the island width evolution calculated using the modified Rutherford equation. Reasonable agreement is obtained during the initial growth of the mode, with a sensible choice of the free parameters in the Rutherford equation. LHCD has a strong stabilising influence, reducing the island width transiently to zero.

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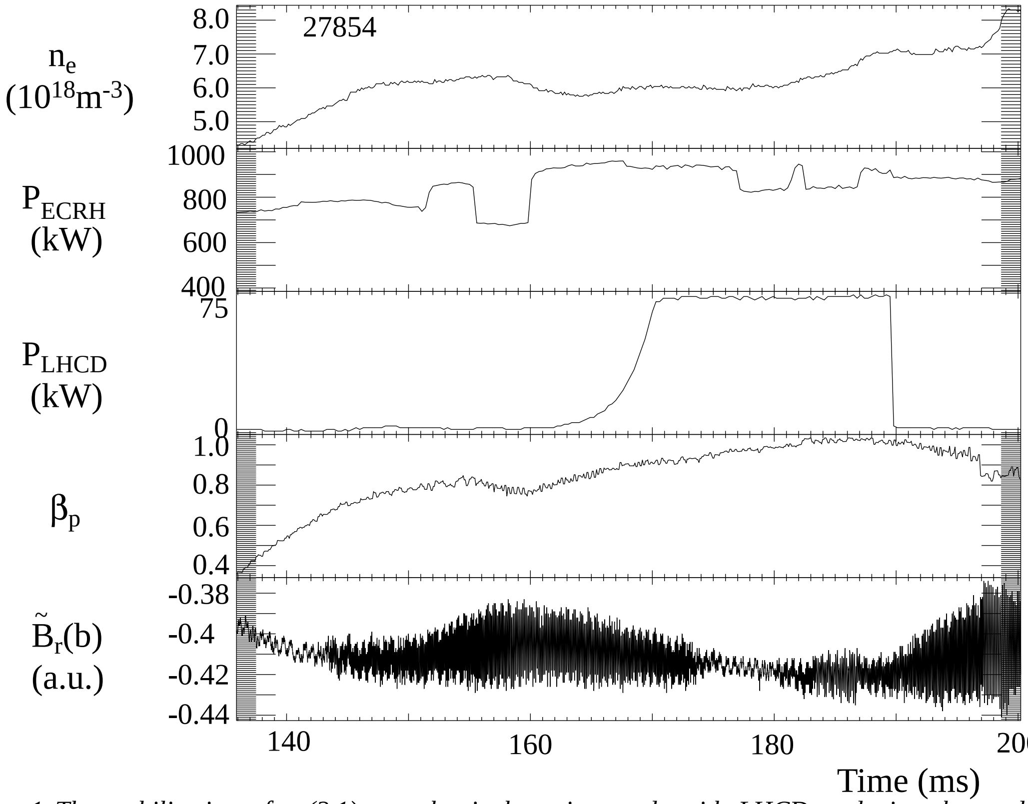

Figure 1 The stabilisation of a (2,1) neo-classical tearing mode with LHCD, reducing the mode amplitude transiently to zero. The mode amplitude increases significantly after the LHCD is switched off. Mode analysis has confirmed that the reduction in MHD activity with LHCD is not due to a change in mode frequency.

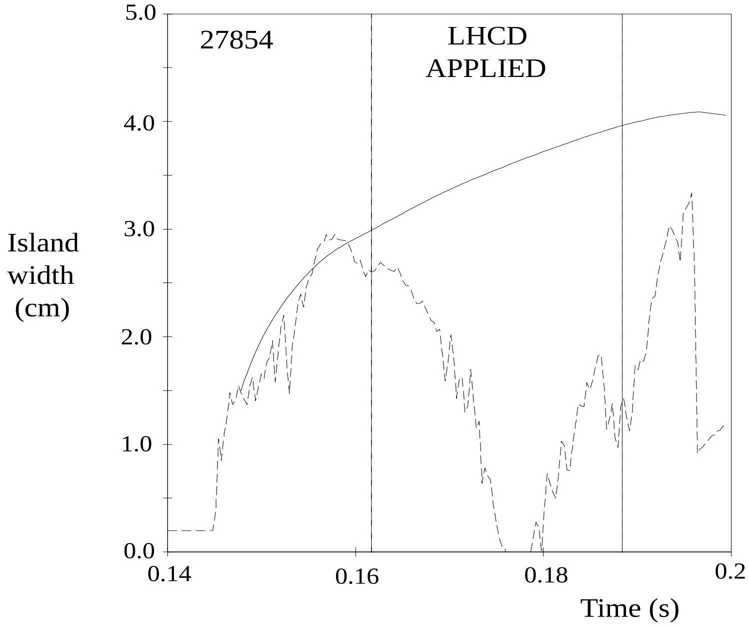

Figure 2 A comparison of the measured (dashed line) and calculated (solid line) neo-classical island width, showing the reduction in island size during LHCD. The parameters used in the Rutherford equation were $r_s\Delta' = -2.5$, $a_1=2$, $a_2=0.1$, $w_c=0.1cm$. The reduction in measured island size well after the LHCD is switched off is due to a reduction in the mode frequency.