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CONTROLLED SEEDING AND STABILISATION OF NEO-CLASSICAL TEARING MODES IN COMPASS-D

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Introduction

Neo-classical tearing modes (NTMs) [1] present one of the most serious limitations to achieving high plasma performance in modern day tokamaks and (probably) next step devices, often restricting the achievable β to values well below the ideal limit. Hence, their control has become an important area of tokamak research. Key to understanding the behaviour and control of NTMs in future devices is a thorough understanding of the onset criteria and instability driving mechanisms. Following earlier COMPASS-D experiments on NTM onset [2] and avoidance/control [3,4], recent experimental studies have focussed on observing how the critical β_p for NTM onset depends upon seed island size and demonstrating the full stabilisation of pre-existing NTMs with Lower Hybrid current drive (LHCD) [5].

Experimental conditions

These experiments were undertaken in typical single null divertor (SND) plasmas on COMPASS-D (I_p ~ 140kA, κ = 1.6, B_ϕ = 1.1T, q_{95} ~ 3.8) at low line averaged electron densities ($0.6\text{-}0.8 \times 10^{19}\text{m}^{-3}$). In excess of 1MW of 60GHz ECRH power was injected into the plasma using balanced launch angles (on both the high and low field side), ensuring no net EC current drive. The low toroidal field used ensured high β regimes could be easily accessed and second harmonic ECRH absorption was concentrated in the plasma core. NTMs were either triggered naturally (e.g. via sawteeth) or using the highly adaptable resonant magnetic perturbation (RMP) external saddle coil set available on COMPASS-D [2]. In addition, the mode stabilisation experiments employed the 1.3GHz LHCD system, launching waves via an eight waveguide conventional antenna ($\Delta\phi$ = -60°, peak launched $N_\parallel$ ~ 2.1 and 77% directivity) [6].

Neo-classical tearing mode seeding conditions and onset criteria

A key aspect of the formation of NTMs is the triggering mechanism which requires a finite seed island (generated by sawteeth for example). As this seeding process depends on various complex physical mechanisms that are hard to measure accurately on most devices, it is difficult to deconvolve the seed size from the other mode activity accompanying the NTM and sawtooth at mode onset. On COMPASS-D it is possible to use the RMP bars to induce measurable seed islands for the NTM, allowing better examination of the underlying physics. The growth of NTMs can be described by the modified Rutherford equation [1],

$$\frac{\tau_r}{r^2}\frac{dw}{dt} = \Delta' + a_{bs}\varepsilon^{1/2}\left(L_q / L_p\right)\frac{\beta_P}{w}\left(\frac{1}{1+w_d^2/w^2} - \frac{w_{pol}^2}{w^2}\right) \qquad (1)$$

This is denoted in terms of the tearing stability parameter (Δ') which is typically negative and therefore stabilising for NTMs and the (β_p/w) expression which represents the reduction of the bootstrap current within the island region that drives the NTM growth (with various profile parameters). τ_r is the resistive time scale. Ion polarisation effects (w_{pol} term) [7] and finite island transport effects (w_d term) [8] act to stabilise the mode at small island sizes, so that a critical seed island size is required for NTM growth. Rearranging equation (1) for NTM onset (i.e. dw/dt=0, $w=w_{seed}$), and neglecting transport effects (which are not significant on COMPASS-D, as discussed in ref [2]), the following is obtained:

$$\beta_{p\text{-onset}} \propto -\Delta' \cdot \frac{w_{seed}}{(1 - w_{pol}^2 / w_{seed}^2)} \qquad (2)$$

In the experiments, the RMP bars induce (2,1) locked modes in the plasma. Once currents in the bars are switched off, the mode quickly spins up and starts to decay in amplitude, producing a rotating island in the plasma, with identifiable structure. The plasma is then heated, and the mode amplitude tracked, mapping the parameter space of the NTM. A set of 28 nominally identical discharges is considered, with the same plasma current and toroidal field, and line average densities in a narrow range (~0.6-0.7 × $10^{19}m^{-3}$). Only the timing and power of the ECRF heating is varied with respect to the switch-off of RMP bar currents. Data was taken once the mode had reached a natural rotation frequency. The resulting island evolutions are shown in Figure 1. This shows that a minimum critical β_p (~0.45) is required for positive growth, and at that critical β_p a critical seed size is necessary (marked '+' in Figure 1). The trajectories divide neatly into two categories, passing to the left or right of the '+'. In some cases, at higher β, a small sawtooth seed can also trigger the NTM.

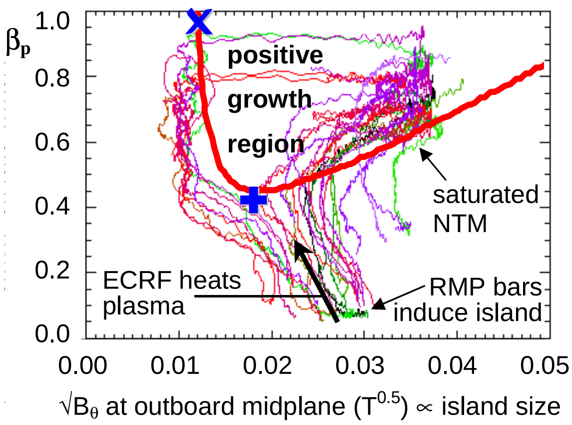

Figure 1: Evolution of RMP induced islands: β_p vs mode amplitude for 28 nominally identical discharges (varying ECRH timing), and predicted onset criteria (thick line). The time increases along lines of increasing β.

The data can be compared with the form of the predicted onset criteria from Eq. (2), where w_{pol} (proportional to ρ_i) is taken as constant (COMPASS-D is electron heated, so ion temperatures remain approximately constant, as confirmed by NPA measurements). The predicted onset criterion is plotted in Figure 1 (adjusted to match the experimental data at minimum $\beta_{p\text{-onset}}$) and reproduces the form of the data reasonably well. In particular, at the lowest β_p where NTMs are triggered (marked '+'), island sizes are approximately $\sqrt{3}$ larger than those required at high β_p (marked '×'), as expected from a solution of equation (2) for minimum $\beta_{p\text{-onset}}$ and maximum (infinite) $\beta_{p\text{-onset}}$. There is some disparity at larger saturated island sizes, where the island might be expected to influence the pressure and current profiles (and thus the Δ' and w_{pol} terms). This would be expected to be stabilising (reducing Δ' and thus the island size), as observed in Figure 1. Toroidal coupling and wall interactions may also play a role as the island size increases. The onset criterion calculated with island transport effects (w_d) included and w_{pol} neglected (not shown in Figure 1) predicts lower threshold island sizes at high β_p, inconsistent with the experimental data.

Neo-classical tearing mode stabilisation with LHCD

In previous COMPASS-D experiments, both the avoidance of (2,1) NTMs [3] and their partial stabilisation [4] with LHCD has been demonstrated. In more recent experiments, NTMs (triggered either naturally or by external RMP coils) have been completely stabilised with modest levels (80-120kW) of launched LHCD power, compared to the ECRH heating power [5]. This is illustrated in Figure 2, where a naturally triggered mode is completely removed with 90kW of LHCD power. Removal of the mode occurs ~10ms after the start of the LHCD pulse, consistent with estimates of the diffusion time for the LH current perturbation (~7ms). The initial appearance of the mode is accompanied by a clear saturation of β_p which continues into the LHCD phase. The loss of ECRH power from one of the gyrotrons (~130kW) during the LH flat top phase (caused by pick-up on its reverse power detector) does initially cause a negligible drop in β, which is immediately followed by a significant increase in β_p (~15%) as the mode is stabilised by the LHCD, achieving a peak β_p~0.95 and β_N~1.6. This increase in performance is maintained until a neo-classical mode re-appears well after the LHCD has been turned off. The delay is again consistent with the calculated LH current diffusion time and the absence of an immediate trigger event for the re-growth of the mode. Complete or partial stabilisation of the NTM in these experiments was observed in 14 shots (see Figure 3). The reduction in the mode amplitude shows a clear dependence on the absorbed LH power (launched power minus the reflected power), normalised to the line averaged density, which is a measure of the LH driven current magnitude. The discontinuous jump in the mode stabilisation (near the point of full stabilisation) is due to a reduction of the neo-classical island below its threshold value.

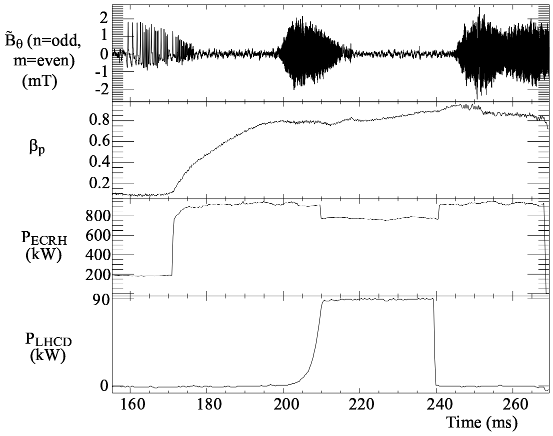

Figure 2: Complete stabilisation of a naturally triggered neo-classical tearing mode (illustrated by the perturbed poloidal magnetic field measurements) with LHCD. A clear improvement in β_p is noted whilst the mode is stabilised.

Estimates of the magnitude and location of the LH driven current have been obtained from the self consistent Fokker Planck and ray tracing code, BANDIT-3D [9] using experimentally measured $T_e(r)$ (T_{e0} ~ 4keV) and $n_e(r)$ profiles. The calculated LH driven current profile is located off-axis (r/a~0.6-0.8) and contributes 15-20% of the plasma current, consistent with the reduction in internal inductance, l_i, deduced from the EFIT equilibrium reconstruction code [10] and from a change in the feedback controlled equilibrium vertical field.

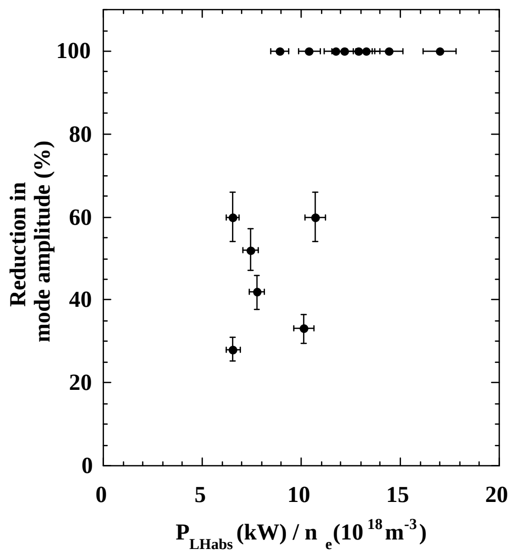

Figure 3: Reduction in mode amplitude as a function of absorbed LH power normalised to electron density (a measure of LH driven current).

Calculations have shown that the observed stabilisation with LHCD on COMPASS-D can be explained by a reduction in Δ' (as suggested in [11]), arising from LH co-current drive at and around the mode rational surface. By adding the calculated LH driven current profiles (at different radial locations) to a reference equilibrium current profile (derived from the TOPEOL free boundary Grad Shafranov equilibrium solver, carefully matched to an EFIT equilibrium reconstruction), new profiles were re-converged and used to calculate cylindrical approximations of $r_s\Delta'$ (where r_s

is the radius of the mode rational surface). A stabilising reduction in $r_s\Delta'$ was calculated when the LH driven current peak was within 3cm (~17% of the minor radius) of the q=2 surface, with the largest reduction (~-3) observed when the LH current peak is situated very close to the rational surface (as is predicted from BANDIT-3D and TOPEOL).

Comparing the island evolution calculated using the modified Rutherford equation (1) to experimentally measured island widths from a standard cylindrical formula [2], an acceptable fit to the initial growth of the island was obtained with reasonable values of $r_s\Delta'$, w_d, w_{pol} and (L_q/L_p). To model the stabilisation of the mode (on a timescale comparable to that observed experimentally) required a relative reduction in $r_s\Delta'$ of between -3 and –4 in equation (1), close to the value predicted by the cylindrical Δ' calculations. Further calculations have also suggested that stabilisation via Δ' is the dominant effect in these experiments as additional ('non-linear' layer) contributions (via a direct current drive mechanism in the island) are small (<15% of the Δ' stabilisation scheme). Toroidal coupling of the q=1 surface can strongly affect the tearing mode stability at q=2 [12]. Indeed, the TOPEOL results show that the q=1 surface is removed with the addition of LHCD. Initial calculations suggest that this can have a strong stabilising effect on Δ' at q=2, although the observed stabilisation timescales are not consistent with this hypothesis. Nevertheless, further experiments are planned to assess the importance of this effect.

Summary

The variation of critical β_p for NTM growth with seed island size has been investigated on COMPASS-D, using externally induced and clearly measurable seed islands, confirming the anticipated theoretical dependence on ion polarisation effects. Full stabilisation of NTMs with LH current drive has been observed, consistent with a modification of the cylindrical approximation to Δ' at the rational surface. The relative change in Δ' calculated with the addition of LHCD agrees well with that required for stabilisation in the Rutherford equation.

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Acknowledgements

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