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Experimental Results on Neoclassical Tearing Mode Stabilization by Radio Frequency Waves

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Abstract. Neoclassical tearing modes (NTMs) may limit performance in Next Step tokamaks, degrading confinement and possibly leading to disruption. In recent years, excellent experimental and theoretical progress has been made in understanding NTMs and their control. The properties of NTMs and various stabilization schemes are described. Recent experimental results on the stabilization of NTMs using radio frequency waves are reviewed and outstanding issues discussed.

INTRODUCTION

Neoclassical tearing modes (NTMs) are observed to limit the achievable long pulse beta to values well below the ideal magneto-hydrodynamic (MHD) limit in low collisionality plasmas. They can degrade confinement (typically by ~ 10 – 30%), may lead to disruption and are a major concern for Next Step tokamaks. The influence of neoclassical effects on resistive tearing modes was predicted in the mid-1980's [1, 2] and NTMs were first identified in TFTR [3] where it was observed that a threshold magnetic island size was required for mode growth. They have subsequently been observed in many other tokamaks [4 and references therein]. In order to fully understand the various NTM stabilization schemes which have been proposed and exploited, it is first of all necessary to briefly review the properties of neoclassical tearing modes.

PROPERTIES OF NEOCLASSICAL TEARING MODES

The growth of NTMs arises from the destabilizing effect of a helical reduction in the bootstrap current due to a local flattening of the pressure profile in the vicinity of the magnetic island structure at a low order rational surface (e.g. where $q = m/n = 3/2$, 2/1). The bootstrap current perturbation is de-stabilizing when $dp/dq < 0$ (NTMs are naturally stable in regions of negative magnetic shear, i.e. when $dp/dq > 0$). At small island sizes other effects [5, 6] act to oppose this drive leading to the requirement of a critical island size w_{crit}, in order for the island to grow. Sawteeth, ELMs and 'fishbone' instabilities have all been observed to trigger NTM instability by generating a 'seed' island $w_{seed} > w_{crit}$ at the relevant NTM rational surface. However, sometimes there is no observable trigger.

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Because of the bootstrap drive, a neoclassical island can grow even when the stability index $\Delta' < 0$ (Δ' is a measure of the magnetic energy available to drive the mode; a classical tearing mode is stable for $\Delta' < 0$). However, there is a critical poloidal beta β_p^{crit} (and hence normalized beta β_N) below which the mode is stable at all island sizes. Island evolution is well-described by the modified Rutherford equation [7], solutions of which are schematically illustrated in Fig. 1. For $\beta_p > \beta_p^{crit}$, the NTM can grow once the seed island exceeds w_{crit}. The mode eventually saturates with a width w_{sat} ($\propto \beta_p/-\Delta'$). Fig. 1 shows that the mode will persist until β_p is reduced to a value β_p^{crit} that is typically much less than the onset value β_p^{onset}.

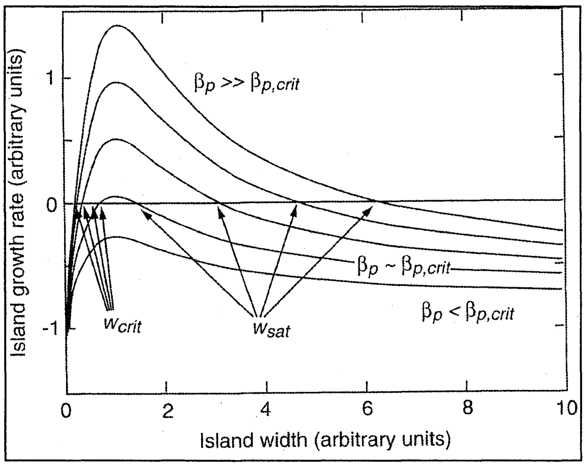

FIGURE 1. Neoclassical mode growth rate (dw/dt) versus island width w for various values of poloidal beta β_p.

STABILIZATION SCHEMES

Various techniques, for which radio frequency waves are particularly suitable, are available to avoid or actively control NTMs. Avoidance techniques include profile control and 'seed' removal. There is concern that alpha particle stabilization effects may lead to large sawteeth in ITER, resulting in a low β_p^{onset} for NTMs. However, both these avoidance techniques are subject to strong constraints from other needs. For example, a stable current profile may not be the optimum for confinement optimization. Similarly, optimum sawtooth and ELM amplitudes are governed by other considerations such as exhaust requirements, divertor power loading etc. Consequently it is prudent to implement schemes for active control.

Active control techniques [8 and references therein] include modification of the equilibrium current profile in the vicinity of the rational surface [9, 10] to decrease the available free energy (Δ' modification) and non-inductive current drive at the island O-point to directly counteract the helical bootstrap current depression. Currents driven well outside the island will reduce the efficiency of either scheme. Consequently, optimization of the driven current *density* j_{CD} and its location with respect to the

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rational surface is required. An efficient control scheme requires that stabilization is achieved with $P_{rf}/P_{tot} << 1$ and on a time-scale $<< \tau_{growth}$, the growth time of the mode. Local *heating* is also expected to contribute an additional stabilizing effect via a change in local plasma resistivity, but direct current drive is expected to be more efficient, especially at small island size. Reference to Fig. 1 indicates that if the island width can be reduced below w_{crit}, the mode should decay naturally.

The fact that magnetic islands typically rotate with frequencies in the range f ~ 100's Hz – 10's kHz suggests that, for optimum effect, modulated injection ('AC scheme') to drive current in phase with the island O-point may be desirable. However, a full theoretical treatment of this problem is very complex since it requires a self-consistent treatment of the wave-plasma interaction and transport effects in the perturbed equilibrium magnetic field. Following detailed consideration of time-dependent effects [11] it has been concluded that the advantages of modulation may be rather limited, especially at high modulation frequencies. Furthermore, it has been shown [12] that even for non-modulated injection ('DC scheme') a large helical component of driven current develops due to transport effects (parallel diffusion of fast electrons generated near the island X-point significantly reduces the driven current density in that region). As a result, the AC and DC schemes are found to have typically a comparable stabilizing effect. Theory generally suggests that a total driven current $I_{CD}/I_p \sim$ few % is adequate for NTM stabilization if optimally localized.

EXPERIMENTAL RESULTS

In the last few years there has been significant experimental progress on the avoidance and control of NTMs using radio frequency power. For example, concerning NTM avoidance, current profile control by electron cyclotron current drive (ECCD) has been used in COMPASS-D [13], TCV [14] and T-10 [15] to increase the critical beta for NTM onset and lower hybrid current drive (LHCD) has also been used to avoid NTMs in COMPASS-D [16]. Sawtooth control has been demonstrated in many devices [17, 18 and references therein]. Recent studies in TCV [19] have shown that an electron cyclotron driven current $I_{ECCD}/I_p \sim 1\%$, located near q = 1 can significantly influence (by a factor x2) the sawtooth period and amplitude. In JET, the direct influence of sawtooth control by ICRF on NTM onset has recently been observed [20]. Central ICRF leads to large sawteeth and a reduced β_p^{onset} compared with NBI heating. On the other hand, with the correct phasing and off-axis resonance, ICRF can reduce the seed island triggered by the sawtooth, leading to an increase in β_N at NTM onset by > 30%.

Full stabilization of m/n = 2/1 NTMs by off-axis LHCD has been demonstrated in high power ECR-heated discharges ($P_{ECH} \sim$ 1MW) in COMPASS-D [21] with $P_{LH}/P_{tot} \sim 10\%$ (Fig. 2) and $I_{LHCD}/I_p \sim 20\%$. Parameter scans showed that the mode amplitude reduction was primarily a function of LH-driven current. Modelling indicated that the LH-driven current (FWHM ~ 0.2a) was centered close to the q = 2 surface in these discharges and that NTM stabilization could be primarily explained by a reduction in Δ', although direct replacement of bootstrap current within the island also contributes a stabilizing effect. One prominent feature of the COMPASS-D experiments is the

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strong beta recovery following NTM stabilization, with β_p increasing up to values 2 x β_p^{onset} in some recent discharges. The stabilizing effect of LHCD is reduced when $j_{LHCD}(r)$ is not optimally located with respect to the q = 2 surface and counter-LHCD has been shown to have no strong stabilizing effect.

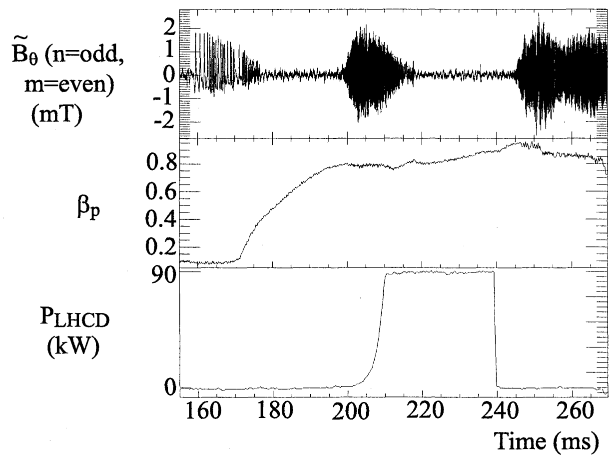

FIGURE 2. Stabilization of m/n = 2/1 neoclassical tearing mode by LHCD in COMPASS-D.

Electron cyclotron current drive has been used to fully stabilize m/n = 3/2 NTMs in ASDEX-U ($P_{ECCD} \leq 1.2$MW, f = 140GHz, $2\omega_{ce}$ X-mode) [22, 23]. The driven current I_{ECCD} was varied by adjustment of the toroidal launch angle and the toroidal magnetic field was ramped by typically ~5-10%, in 1s, i.e. slowly compared to the island growth time, in order to fine tune the radial position of the absorption location. The optimum toroidal launch angle was determined by the need to maximize the driven current density at the island location. At $\beta_N \sim 2.2$–2.5, a power level $P_{ECCD}/P_{tot} \sim 10\%$ was sufficient for full stabilization of the m/n = 3/2 NTM (Fig. 3).

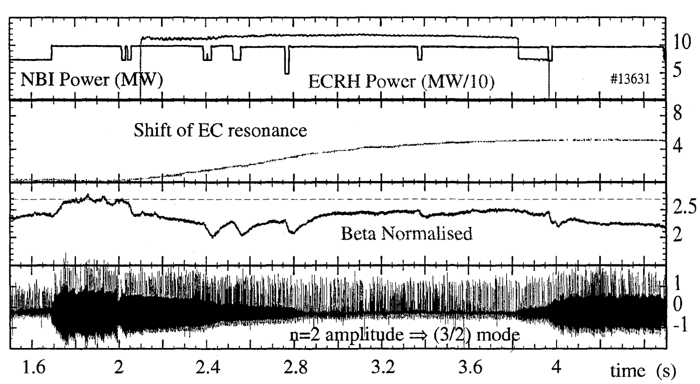

FIGURE 3. Stabilization of m/n = 3/2 neoclassical tearing mode by ECCD in ASDEX-U.

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The radial location of driven current had to be accurate within ~ ± 2cm. Pure electron cyclotron heating, under similar conditions, had little effect. Similarly, at a power level sufficient for complete stabilization with co-ECCD, counter-ECCD had little effect on mode amplitude. In ASDEX-U, modulated and non-modulated ECCD exhibited similar stabilization efficiency for the same peak power, in agreement with modelling [12] which also shows that the main stabilizing effect comes from direct generation of helical current (~ 15–20kA) within the island by ECCD; Δ' variations can only account for ~ 10-20% of the stabilizing effect. Although the mode is completely stabilized, β does not recover to its full value at mode onset; this is attributed to confinement degradation during ECRH/ECCD.

Second harmonic ECCD (110GHz, P_{ECCD} ~ 1.1MW) has also been used to fully stabilize m/n = 3/2 NTMs in DIII-D [24], in an ELMing H-mode target plasma. As in the case of ASDEX-U, a modest toroidal launch angle was employed to maximize j_{ECCD} and the two microwave beams were directed to interact with the magnetic island on the high field side of the plasma magnetic axis to minimize electron trapping effects on the current drive efficiency. Motional Stark Effect (MSE) measurements showed that the driven current was radially localized to a region of width $\delta \sim w_{sat}$. The m/n = 3/2 NTM was fully stabilized with DC injection (Fig. 4), the mode amplitude decreasing rapidly below a certain level, presumably corresponding to $w \sim w_{crit}$. For a strong stabilizing effect, the driven current had to be accurately located within ~ 2cm. When the NTM was stabilized, the plasma pressure increased by an amount double that expected from the additional electron cyclotron power. As in other experiments, counter current drive had little effect on the mode amplitude.

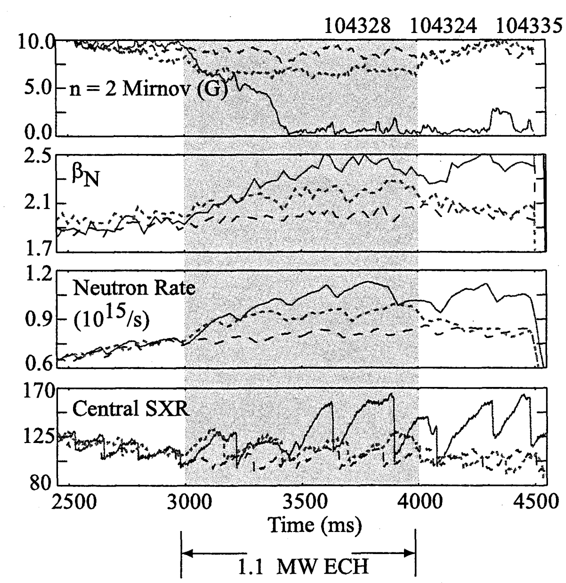

FIGURE 4. Stabilization of m/n = 3/2 NTM by ECCD at the q = 3/2 surface in DIII-D (solid lines). Also shown are the effect of displacing the ECCD by 2cm (dotted lines) and a case without ECCD (dashed lines).

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In JT-60U the m/n = 3/2 NTM has been fully stabilized [25, 26] using fundamental O-mode ECCD (110GHz), the scheme envisaged for ITER. Full stabilization was achieved with $P_{ECCD}/P_{tot} \sim 17\%$ and $I_{ECCD}/I_p \sim 2\%$ (Fig. 5). However, with the available ECRF power, full stabilization was only achieved in the presence of a step down in NBI power, thereby reducing β_N to a value significantly below that at NTM onset. DC injection was used and the width of the EC-driven current density profile was comparable to the magnetic island width. The location of driven current is very sensitive to the launch angle and in JT-60U the launch angle could be varied during a discharge to identify the optimum angle. Full stabilization was achieved with fixed optimum launch angle. Variation of the launch angle from the optimum by 0.5°, corresponding to a shift of the peak driven current location by ~ w/2, increased the stabilization time from ~ 0.7s to ~ 2s. NTM stabilization resulted in an enhancement of the plasma stored energy and neutron emission rate by ~ 12% and ~ 18% respectively compared to a case without ECCD.

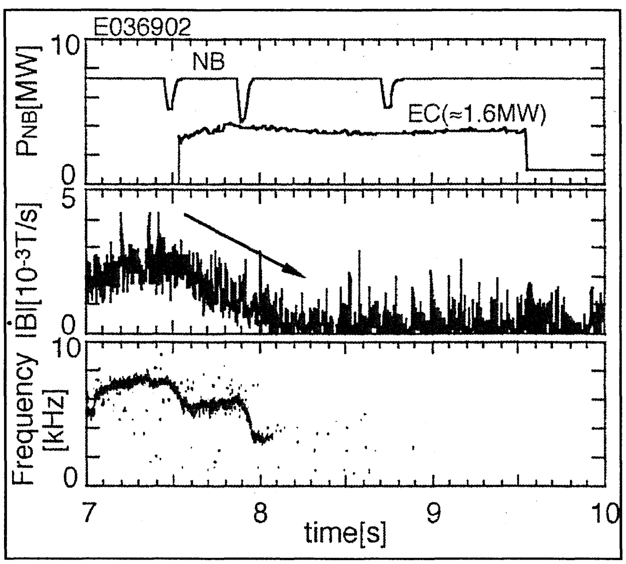

FIGURE 5. Stabilization of m/n = 3/2 neoclassical tearing mode by ECCD in JT-60U.

Finally, it should be noted that m/n = 2/1 tearing modes with significant neoclassical drive have been stabilized using ECRH (140GHz) in FTU [27] leading to a significant improvement in core energy confinement. The ECRH deposition width δ_{abs}, was also of the order of the island width and effective stabilization required that the EC power deposition was aligned to the island O-point to a precision of order $\delta_{abs} \sim w$. In the conditions of these experiments the dominant contribution to stabilization was from heating rather than current drive. The minimum power required for stabilization was of order $P_{ECH} \sim 0.15 P_{OH}$.

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SUMMARY & CONCLUSIONS

Both 'seed' control and current/pressure profile control have been shown to be effective for avoiding or deferring NTM onset. However, both these schemes are subject to constraints arising from other demands of high performance tokamak operation. Therefore it is prudent to develop effective active control techniques. Control of the equilibrium current profile by LHCD has been shown to be effective for stabilization of m/n = 2/1 NTMs enabling β_p (hence also β_N) to be increased to values well in excess of those at mode onset. Stabilization of the m/n = 3/2 NTM by ECCD in the island O-point has been demonstrated in a number of experiments. Key features of these experiments include:

- launch conditions chosen to optimize driven current density,
- driven current localized to a region of width $\delta \sim w_{sat}$,
- effect of ECCD dominates that of heating,
- DC scheme is as effective as ECCD modulated in phase with the island,
- stabilization typically requires $P_{ECCD}/P_{tot} \sim 10$ - 20%, $I_{ECCD}/I_p \sim$ few %,
- stabilization sensitive to current drive location to a precision $\sim \delta \sim w_{sat}$
- stabilization accompanied by incomplete beta recovery ($\beta < \beta^{onset}$)

These observations are generally in good agreement with theory. In a Next Step device such as ITER-FEAT, where the NTM growth time is expected to be 100s or more there is appreciable time to react. However, it is necessary to develop a *robust* active control system subject to demanding engineering constraints. Experimental results reported so far represent an excellent proof-of-principle demonstration of active control techniques but often rely on techniques such as toroidal field ramping to establish optimum radial localization of the driven current or heating power step-down to amplify the effectiveness of the driven current. In future it will be desirable to demonstrate real time control, involving mode detection, identification of mode location and beam steering during the discharge to maintain an optimum driven current perturbation for mode suppression. Furthermore, it is important to conduct such studies in high performance plasmas and to demonstrate significant beta recovery as a result of mode suppression. It is important to further investigate the relative effectiveness of the DC and AC stabilization schemes and to consider the effects of mode locking which could occur on a much shorter time-scale than the NTM growth time.

It is necessary to explore whether simultaneous control of NTMs with different poloidal/toroidal mode numbers will be required in a Next Step device. In some experiments there is evidence that NTMs with different mode numbers do not co-exist [28].

Finally there are outstanding questions relating to RF propagation and absorption. Although LHCD is effective for off-axis current drive, there are limited possibilities to control the current drive location which limit its potential effectiveness as a robust control tool. On the other hand, ECCD offers tremendous flexibility but trapping effects are a concern at large minor radius. These can partly be alleviated by off-mid-plane injection but engineering constraints for such a scheme are significant in a device such as ITER-FEAT, so it is important to determine whether off-mid-plane launch is essential.

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