Complete Stabilization of Neoclassical Tearing Modes with Lower Hybrid Current Drive on COMPASS-D

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Lower hybrid current drive (LHCD) with modest powers (~10% of the total power input) has been used for the first time to completely stabilize performance limiting neoclassical tearing modes in many COMPASS-D tokamak discharges. The stabilizing effect in these experiments is consistent with a reduction in the free energy available in the current profile to drive tearing modes (i.e., the stability index, Δ') resulting from favorable current gradients (from the LHCD driven current) around the rational surface.

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Neoclassical tearing modes [1] are instabilities in tokamaks observed at low collisionality, driven by the plasma pressure gradient, which destroy the nested magnetic surfaces, degrading confinement and sometimes leading to a disruption. Their growth 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 neoclassical magnetic island structure [1]. They have been observed on many tokamaks (COMPASS-D [2], TFTR [3], DIII-D [4], ASDEX-Upgrade [5], etc.) and limit the achievable β (ratio of the thermal and magnetic pressures) to values well below the ideal magnetohydrodynamic (MHD) Troyon limit [6], in low collisionality plasmas. It is predicted that neoclassical tearing modes may be unstable in next step tokamaks, limiting the achievable plasma performance. Hence, their stabilization has recently become an active and important area of tokamak plasma research.

In recent experiments on COMPASS-D, lower hybrid current drive (LHCD) has been successfully used for the first time to reliably and completely stabilize neoclassical tearing modes in high β plasmas established using high power electron cyclotron resonance heating (ECRH). Stabilization results in a significant increase in the plasma performance (increasing β by ~15%–20%) and is achieved with an LHCD power of just 10% of the total ECRH heating power (>1 MW).

The stabilization experiments described in this Letter are closely based on previous studies that rigorously identified performance limiting magnetic islands observed on COMPASS-D as neoclassical, by carefully comparing their behavior with predictions from neoclassical tearing mode theory [2]. This theory is characterized by the modified Rutherford equation, which formulates the time evolution of the island width, w, as follows [1,7]:

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

where η_{nc} is the neoclassical resistivity and a_1 and a_2 are parameters dependent on the equilibrium profiles. The nonlinear stability index, Δ' [8], represents the free energy in the equilibrium current profile. The second term represents the neoclassical bootstrap current drive for the island growth, where β_p is the ratio of thermal and poloidal magnetic field pressures and w_c parametrizes the contribution from the $\chi_\parallel/\chi_\perp$ stabilizing effect [9]. The third term denotes the contribution from the ion polarization current [10] where $\rho_{\theta i}$ is the poloidal ion Larmor radius and $g(\varepsilon, \nu_i)$ is a function of inverse aspect ratio ε and an ion collisionality parameter, ν_i.

Two stabilization mechanisms have been identified from theory. In the first, an externally driven current localized in the island structure [11,12] is used to replace the "missing" bootstrap current. Alternatively, the addition of a cocurrent perturbation at, or close to, the mode rational surface steepens (flattens or reverses) the equilibrium current gradients outside (inside) the surface, resulting in a reduction in the free energy available in the equilibrium current profile (parametrized by Δ') [13]. This reduction occurs if the peak of the current perturbation is located within $0.9 \times \sigma$ of the rational surface, where σ is the Gaussian half width (at $1/e$ height) of the current perturbation. The COMPASS-D LHCD system is ideally suited to test stabilization by a modification of Δ' as confirmed by the experimental results shown in this Letter.

The COMPASS-D tokamak [2] (major radius, $R_0 = 0.557$ m, minor radius, $a \sim 0.18$ m, $\varepsilon \sim 0.3$) is equipped with powerful 60 GHz ECRH [14] and 1.3 GHz LHCD [15] microwave systems (the latter with a peak launched $N_\parallel = 2.1$). Typical single null divertor plasma parameters employed in these experiments were plasma current, $I_p \sim 140$ kA maintained by feedback control, toroidal field at R_0, $B_\phi = 1.1$ T, edge safety factor, $q_{95} \sim 3.8$, elongation, $\kappa \sim 1.6$, and line averaged electron density, $\overline{n}_e \sim (0.6–0.8) \times 10^{19}$ m^{-3}. In excess of 1 MW of ECRH power was launched with balanced injection angles (on both the high field side and low field side antennas), ensuring there was no significant net electron cyclotron driven

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current. The low toroidal field used in these experiments allowed access to high β regimes and ensured second harmonic ECRH absorption was localized in the plasma core.

The onset of an ($m = 2$, $n = 1$) neoclassical tearing mode (where m is the poloidal mode number and n is the toroidal mode number) was consistently observed during high power ECRH in the present discharges, triggered either by a natural MHD event (such as a sawtooth) or by a decaying (2, 1) magnetic island induced using external saddle coils [2]. The positive identification of these modes as neoclassical tearing modes is described in Ref. [2]. Complete stabilization of these modes was always achieved (on many discharges) with modest levels of LHCD launched power (80–120 kW) compared to the ECRH heating power (>1 MW). An example is shown in Fig. 1 where a naturally triggered neoclassical mode (observed in the $m =$ even, $n =$ odd component of the perturbed poloidal magnetic field) is completely removed by the application of LHCD power (90 kW). Removal of the mode occurs ~10 ms after the start of the LHCD pulse consistent with estimates of the diffusion time for the LH driven current perturbation (~7 ms). The initial appearance of the mode is characterized by a clear saturation of β_p (measured by a diamagnetic loop) which persists into the LHCD pulse. The LH flattop phase is accompanied by a loss of ECRH power (~130 kW) from one of the gyrotrons (caused by pickup on its reverse power detector). Although not intentional, this does, in fact, ensure that the total rf input power is maintained at an approximately constant level. The loss of ECRH power in this way causes a negligible initial drop in β, which is rapidly followed by a significant increase in β_p (~15% in this shot) as the mode is stabilized by the LHCD. *The fact that the mode is decaying despite a rise in β_p is clear evidence for LHCD stabilization.* β_p continues to rise [achieving a peak $\beta_p \sim 0.95$ and beta normalized to (I_p/aB_ϕ), $\beta_N \sim 1.6$] until the neoclassical mode reappears, well after the LHCD pulse has finished. The delay between the end of the LHCD pulse and the reappearance of the neoclassical mode (5 ms in this case) is again consistent with the calculated LH current diffusion time but could also be attributed to the absence of an immediate trigger for the regrowth of the mode.

The threshold LHCD power for complete stabilization (~80 kW) in these experiments was obtained from several detailed power scans. Lower levels of LHCD launched power (~70 kW or less) resulted in only a partial stabilization of the mode [16], accompanied by an increase in mode amplitude after LHCD switch-off. The LHCD power required for full stabilization increases with increasing line averaged electron density within the narrow operating range [$(0.6–0.8) \times 10^{19}$ m^{-3}], consistent with the fact that the magnitude of the LH driven current (which is proportional to the LH power normalized to the density) is the dominant factor in the stabilization. Figure 2 shows the reduction in mode amplitude as a function of LH absorbed power (injected LH power minus reflected power), normalized to the line averaged density. The discontinuous jump in the reduction of mode amplitude as the LHCD power is increased is evidence of the island width being reduced below the threshold level [10], thus causing the mode to decay naturally.

Estimates of the LH driven current profile have been obtained using the relativistic and self-consistent Fokker Planck and ray tracing code, BANDIT-3D [17], using measured electron temperature, $T_e(r)$, and density, $n_e(r)$, profiles from Thomson scattering. The measured $T_e(r)$ profile is strongly peaked during ECRH ($T_{e0} \sim 4$ keV), reflecting the strong damping in the plasma core. The measured $n_e(r)$ profiles are very broad, as previously observed during high power ECRH on COMPASS-D [18]. Neither $n_e(r)$ nor $T_e(r)$ profiles show any significant change during the LHCD phase.

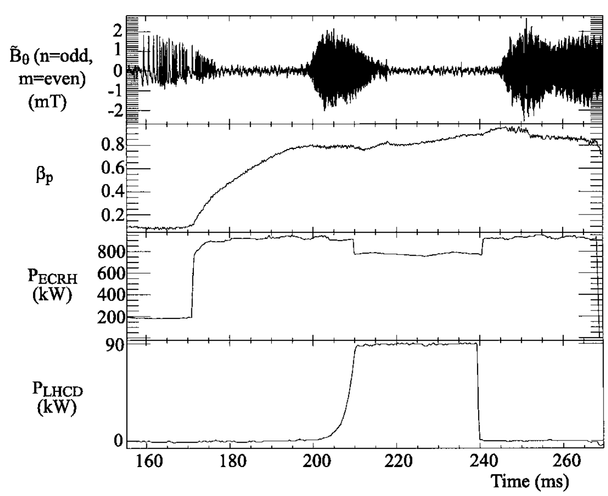

FIG. 1. The stabilizing effect of LHCD on a naturally triggered neoclassical tearing mode (shot 28 601). A clear improvement in performance (indicated by an increase in β_p) is observed during and after the mode (shown on the top trace) stabilization.

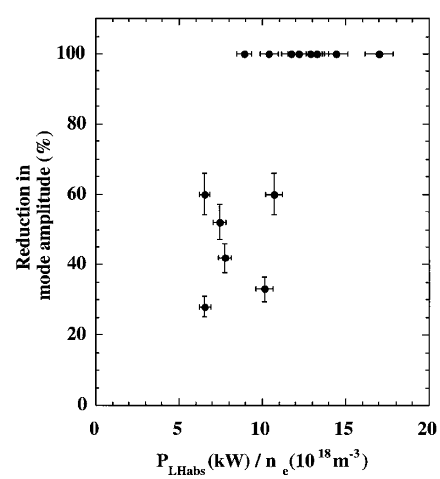

FIG. 2. Graph showing the reduction in amplitude of the neoclassical tearing mode for different discharges plotted against the absorbed LH power, normalized to the line averaged density.

The off-axis LH driven current (~20% of I_p) from BANDIT-3D (see Fig. 3) is consistent with the observed reduction in the plasma internal inductance, l_i, from 1.9 to 1.7 during the LH phase, indicating a slight overall broadening of the total current profile. This has been noted in EFIT [19] equilibrium reconstructions and is also consistent with simple estimates from the small change in the feedback-controlled vertical field required to maintain the radial plasma position. The high overall values of l_i indicate peaked current profiles, in accordance with the peaked $T_e(r)$ profiles. Calculations show that the observed mode stabilization with LHCD can be explained via a reduction in Δ', brought about by a modification to the equilibrium current profile. A reference equilibrium current profile (with no LHCD) was derived using the TOPEOL code (a free boundary Grad-Shafranov equilibrium solver) carefully matched to an EFIT equilibrium reconstruction which uses experimental poloidal field coil currents and magnetic detector signals. The LH driven current, determined by BANDIT-3D, was added and the equilibrium reconverged, conserving the total plasma current (which is controlled during the experiments). The change in l_i indicated by TOPEOL with the addition of LHCD agrees well with EFIT output. The location of the $q = 2$ surface predicted in these simulations (both with and without LHCD) is $r/a \sim 0.7$–0.8.

The perturbed current profiles were used to calculate a cylindrical approximation to $r_s\Delta'$ (where r_s is the radius of the $q = 2$ surface). Figure 4 shows values of $r_s\Delta'$ plotted against the assumed position of the current perturbation peak with respect to the location of the $q = 2$ surface. As expected, the largest relative reduction in $r_s\Delta'$ (~ -3) is observed when the center of the current perturbation is located at, or very close to, the $q = 2$ surface. Stabilizing reductions in $r_s\Delta'$ are also obtained when the current peak is displaced over a range of 3 cm around the rational surface. This is equivalent to ~17% of the minor radius on COMPASS-D. Indeed, the calculated position of the LH driven current profile from BANDIT-3D (indicated by the diamond in Fig. 4) is very close to the evolved position of the $q = 2$ surface deduced from TOPEOL, resulting in a maximum reduction of $r_s\Delta'$ in these experiments.

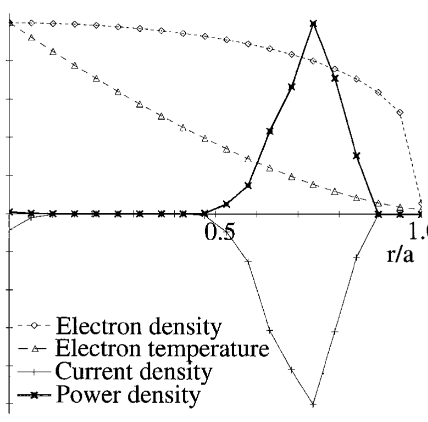

FIG. 3. Results of a BANDIT-3D simulation, using experimentally measured $n_e(r)$ and $T_e(r)$ profiles, showing the calculated, normalized off-axis LH power density absorbed and current density profiles. The negative driven current implies cocurrent drive.

It is of interest to examine how these estimates of the relative change in $r_s\Delta'$ due to LHCD influence the evolution of the neoclassical tearing modes. Thus, the evolution of the island width was calculated from the modified Rutherford equation [see Eq. (1)] and compared to estimates of the measured island width, determined using a standard cylindrical formula [defined in Eq. (6) in Ref. [2]].

An acceptable fit to the initial growth of the island is shown in Fig. 5(a). At the onset of the LHCD pulse, with a_1, a_2, and w_c fixed, a reduction in $r_s\Delta'$ of -3 (from -2 to -5) is required for stabilization of the mode on a time scale comparable to that observed experimentally [see Fig. 5(b)]. This agrees well with the calculated relative change in $r_s\Delta'$ with LHCD added. It should be noted that the current profile evolution with LHCD predicted by TOPEOL tends to move the $q = 2$ surface inwards somewhat, to a region of lower magnetic shear (s). However, further calculations show that the resultant changes in a_1 and a_2 do not significantly affect the relative change in $r_s\Delta'$ required for stabilization on the observed time scale. The relatively broad spatial range of driven current locations over which $r_s\Delta'$ is predicted to be reduced suggests this stabilization scheme will be robust to modest changes in the position of the LHCD current peak and/or the $q = 2$ surface.

While stabilization via a modification of Δ' [13] can account for the experimental results, in principle there are other mechanisms which could contribute. The removal of the $q = 1$ tearing surface (shown to occur in TOPEOL with the addition of LHCD) can, according to one model [20], have a stabilizing influence on the $q = 2$ surface, and this may enhance the Δ' stabilization effect observed. Also, LHCD contributes to the direct replacement of the

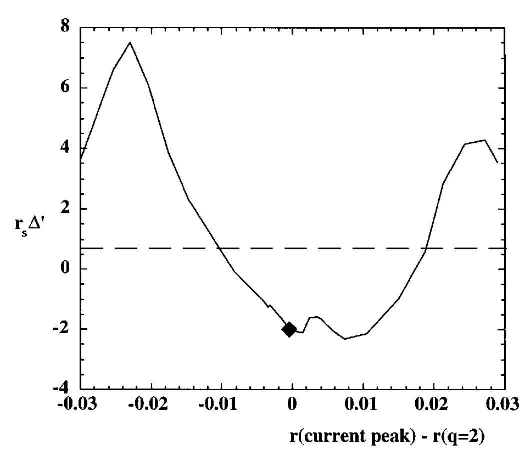

FIG. 4. Values of $r_s\Delta'$ plotted against the radial location of the LH driven current perturbation relative to the rational surface. A stabilizing influence (reduction in $r_s\Delta'$ compared to the unperturbed current profile case, shown with a horizontal dotted line) is noted over a $3cm$ spatial range. ◆ denotes the reduction in $r_s\Delta'$ for the BANDIT-3D estimate of the experimental LH driven current profile.

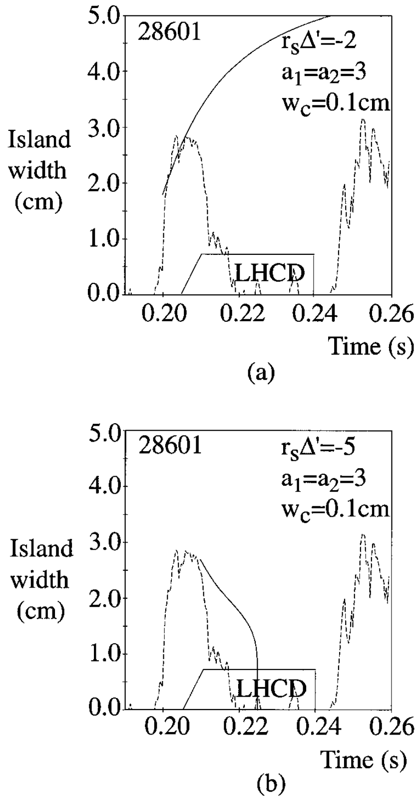

FIG. 5. (a) and (b) Evolution of both the measured island width (dotted line) determined from external saddle coil information and calculated island width (solid line) determined from a solution of the modified Rutherford equation with different values of $r_s\Delta'$ assumed.

missing bootstrap current with driven current within the island [12] which has been shown to have a stabilizing effect on MHD modes in recent modeling [21] and experimental observations with electron cyclotron current drive (ECCD) in ASDEX-Upgrade [22] and COMPASS-D [23]. However, LHCD is generally not as localized as ECCD, and in these experiments, the driven current extends beyond the island. In this case, analytic calculations indicate the dominant effect is accounted for in the Δ' calculation and any additional ("nonlinear" layer) contribution to Eq. (1) is small [$\sim(w/\delta)^2 < 15\%$, where δ is the full width of the LH driven current].

BANDIT-3D simulations of LH driven current in ITER advanced tokamak regimes [24] ($I_p = 12$ MA, frequency, $f = 5$ GHz, outboard midplane launch, LH power = 50 MW) indicate 10%–15% of the plasma current can be driven in the region of the expected location of $q = 2$ ($r/a \sim 0.6$–0.8). This suggests LHCD or any other off-axis current drive scheme could be a possible candidate for the stabilization of neoclassical tearing modes, via a modification to Δ', on next step devices. This could complement or enhance proposed stabilization techniques using ECCD.

In summary, the complete stabilization of (2, 1) neoclassical tearing modes has been reproducibly demonstrated on COMPASS-D with modest levels of LHCD power (80–120 kW). Calculations indicate that the LH driven current profile results in a reduction in $r_s\Delta'$ of ~ -3 which is sufficient, on its own, to stabilize the mode (reducing the island width to zero) as suggested theoretically [13].

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[1] O. Sauter *et al.,* Phys. Plasmas **4**, 1654 (1997).
[2] D. A. Gates *et al.,* Nucl. Fusion **37**, 1593 (1997).
[3] Z. Chang *et al.,* Phys. Rev. Lett. **74**, 4663 (1995).
[4] R. J. LaHaye *et al.,* Nucl. Fusion **37**, 397 (1997).
[5] H. Zohm *et al.,* Plasma Phys. Controlled Fusion **39**, B237 (1997).
[6] F. Troyon *et al.,* Phys. Lett. **110A**, 29 (1985).
[7] H. R. Wilson *et al.,* Plasma Phys. Controlled Fusion **38**, A149 (1996).
[8] P. H. Rutherford, Phys. Fluids **16**, 1903 (1973).
[9] R. Fitzpatrick *et al.,* Phys. Plasmas **2**, 825 (1995).
[10] H. R. Wilson *et al.,* Phys. Plasmas **3**, 248 (1996).
[11] A. W. Morris *et al.,* in *Proceedings of the 19th EPS Conference on Controlled Fusion and Plasma Physics, Innsbruck, 1992* (Pergamon, New York, 1992).
[12] C. C. Hegna and J. D. Callen, Phys. Plasmas **4**, 2940 (1997).
[13] A. Pletzer and F. W. Perkins, Phys. Plasmas **6**, 1589 (1999).
[14] G. A. Whitehurst *et al.,* in *Proceedings of the 22nd EPS Conference on Controlled Fusion and Plasma Physics, Bournemouth, 1995* (MIT, Cambridge, MA, 1995).
[15] C. D. Warrick *et al.,* in *Proceedings of the 22nd EPS Conference on Controlled Fusion and Plasma Physics, Bournemouth, 1995* (Ref. [14]).
[16] C. D. Warrick *et al.,* in *Proceedings of the 26th EPS Conference on Controlled Fusion and Plasma Physics, Maastricht, 1999* (Institute of Physics Publishing, Bristol, U.K., 1999).
[17] M. R. O'Brien *et al.,* in *Proceedings of the IAEA Technical Committee Meeting on Advances in Simulation and Modelling Thermonuclear Plasmas, Montreal, 1992* (International Atomic Energy Agency, Vienna, 1993), p. 527.
[18] C. D. Warrick *et al.,* in *Proceedings of the 1998 ICPP and 25th EPS Conference on Controlled Fusion and Plasma Physics, Prague, 1998* (Czech Technical University Prague Publishing Center, Prague, 1998).
[19] L. Lao *et al.,* Nucl. Fusion **25**, 1611 (1985).
[20] J. W. Connor *et al.,* in *Proceedings of the 19th EPS Conference on Controlled Fusion and Plasma Physics, Innsbruck, 1992* (Ref. [11]).
[21] G. Giruzzi *et al.,* Nucl. Fusion **39**, 107 (1999).
[22] S. Gunter *et al.,* in *Proceedings of the 26th EPS Conference on Controlled Fusion and Plasma Physics, Maastricht, 1999* (Ref. [16]).
[23] G. J. McArdle *et al.,* in *Proceedings of the 9th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Heating, Borrego Springs, 1995* (World Scientific, River Edge, NJ, 1995).
[24] ITER Detailed Design Report, 1996.