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The Role of the m/n=3/2 Tearing Mode in the Hybrid Scenario and Extension of the Hybrid Operating Regime

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Abstract

The DIII-D realization of the proposed ITER hybrid scenario has a small, stationary *m/n=3/2* NTM associated with it. These plasmas, with q95>4, also show q0≥1 without sawteeth (or with very small sawteeth for q95≈4). We conjecture that one effect of the 3/2 NTM is to regulate the central value of q, via the rapid increase in the *m/n=2/2* sideband as q0→1. We present evidence for the coupling between the 3/2 mode island width and q0, and discuss several possible mechanisms for the physical mechanism connecting the NTM and the current profile.

Introduction

The hybrid scenario has been proposed as a robust tokamak operating scenario for high performance operation of ITER [1]. The purpose of this scenario is to provide the maximum neutron fluence per ITER pulse. In its performance characteristics it is intermediate between the standard, high current, ELMy H-mode scenario [2], and the steady-state Advanced Tokamak scenarios [3], hence the name "hybrid". In this scenario the plasma is stationary – profiles of density, temperature, and current do not change with time – but not steady-state because the transformer provides a significant fraction of the plasma current. Projections to ITER based on DIII-D hybrid discharges indicate that a pulse length longer than 1 hour should be achievable, with a power gain Q ≥ 10 [4].

Compared to the standard, ELMy H-mode, the hybrid scenario plasma provides better confinement at the same current, or equivalent confinement at lower current. Using the latter condition reduces the transformer requirements and allows longer pulse length. The hybrid scenario also allows stable operation to a higher level of β, yielding higher gain (Q). Several realizations of the hybrid scenario have been reported, from DIII-D, ASDEX-U [5], JET [6], and JT-60U [7]. Here we will focus on characterization and on the physical mechanisms of the DIII-D realization.

In order to confidently extrapolate the hybrid scenario to ITER operation it is important to develop a better understanding of the physical mechanisms linking the equilibrium configuration, MHD stability, and turbulence in this specific case. We have demonstrated that an improved stationary state exists, and have shown that it can be produced over a wide range of basic plasma parameters. The next step is to understand the processes which sustain this state so that reliable predictive models can be developed.

Observations of the hybrid plasma

The DIII-D program has done extensive studies of the operating regime for the hybrid scenario [8]. In DIII-D, hybrid operation is characterized by low current; the safety factor at the 95% poloidal flux surface is q95 ≥ 4. The central current density is lower and the central safety factor is higher than is expected for comparable conventional scenario plasmas. The central safety factor is generally above, but very close to unity: q0=1+ε with ε≤0.05. Sawteeth are either absent (q95>4) or barely detectable (q94≈4), and have no noticeable effect. The reduced sawtooth amplitude reduces or eliminates a trigger for the deleterious *m=2*, *n=1* neoclassical tearing mode. The 2/1 mode limits the achievable beta in the conventional H-mode scenario. The hybrid plasmas show good confinement, with confinement factors [9] H_{89p} up to 2.8 and H_{98y2} up to 1.7 with proper correction of the static error fields. There is no local region of particularly good confinement other than the H-mode pedestal near the edge. Rather, the χ_i and χ_e profiles are flat across the plasma, more so than in typical H-mode operation.

A key feature of the hybrid scenario in DIII-D is the presence of an *m=3*, *n=2* neoclassical tearing mode (NTM). We conjecture that this nonlinearly saturated mode is responsible for modification of the current and safety factor profiles in such a way as to improve both the beta limits and the confinement. In this paper we examine the characteristics of the 3/2 NTM, and discuss several possible mechanisms that may link the NTM to the current profile. We focus our attention here on the interaction between the 3/2 NTM, the current density profile near the magnetic axis and the reduction or elimination of sawteeth. The examination of the effect of the 3/2 NTM on the q-profile in the outer half of the plasma, and possibe advantageous effects on confinement will be discussed in future publications.

Connecting the NTM and the q profile

The key to producing a hybrid plasma in DIII-D is to raise β early in the discharge evolution. This initiates an early H-mode, minimizes the ELM-free period, and triggers a 3/2 NTM before q0 falls to 1 and sawtoothing begins (Figure 1). If the sawtooth process is allowed to start, a standard H-mode configuration results. With the 3/2 mode, the current density is maintained at the level needed to keep q0 just above 1. An understanding of the hybrid scenario requires an explanation for the regulation of q0 at this particular value.

This observation is not accidental. Calculation of the components of the current profile indicates that the known contributions from the Ohmic, bootstrap, and neutral beam driven currents adds up to more than is observed, with the excess inside the q=3/2 surface (Figure 2). This is confirmed by simulations of the current profile evolution using the observed profiles as initial conditions. The computed current becomes significantly more peaked at the axis with time.

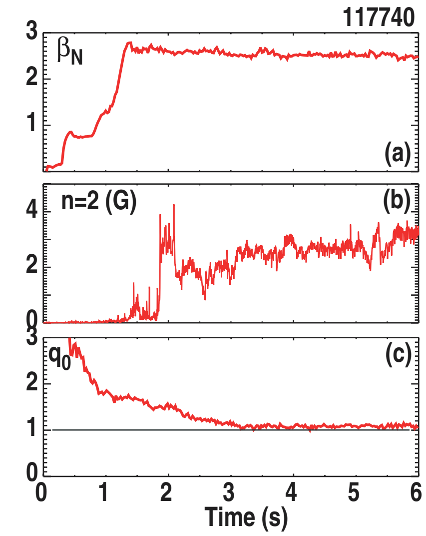

Fig. 1. Evolution of a hybrid scenario discharge in DIII-D. (a) Normalized $b_N = b(\%)aB/I(MA)$. The pressure is raised early to induce H-mode and to start the m/n=3/2 NTM before sawteeth begin/ (b) The r.m.s. amplitude at the Mirnov probes of the n=2 toroidal harmonic, as generated by the 3/2 NTM. (c) The safety factor on the magnetic axis which reaches a stationary condition slightly above 1.

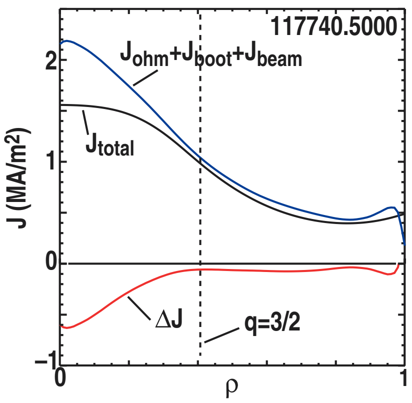

Fig. 2. Components of the current profile, averaged for 0.5 s during the stationary portion of a hybrid discharge. The total current (J_{total}; black) is obtained from EFIT equilibrium reconstruction. The computed current ($J_{ohm}+J_{boot}+J_{beam}$; blue) is calculated using the measured n_e, T_e, T_i, and Z_{eff} profiles in models of the Ohmic, bootstrap and beam-driven currents, respectively. The sum is the expected current profile. The difference (DJ; red) is the non-classical current attributed to the presence of the 3/2 NTM. The total non-classical current inside the q=1.5 surface (dashed line) is approximately 50 kA.

Both the observed and calculated structure of the NTM indicate that it can be responsible for the regulation of q0 (Figure 3). We are able to measure both the density and temperature fluctuations associated with the NTM. Near the q=1.5 surface, on the outboard side, both $\delta n_e/n_e$ and δT_e show the expected amplitude and phase signatures of an island structure. In this experiment, the δn_e diagnostic has finer spatial resolution but covers a much smaller portion of the plasma. The δT_e measurement also shows the island structure on the inboard side of the axis, with small amplitude and a phase corresponding to the odd (m=3) poloidal mode number. Near the axis, the temperature perturbation is still large, about 1/3 of the peak value at the 3/2 island, and it lags the peak near the island by about $2\pi/3$.

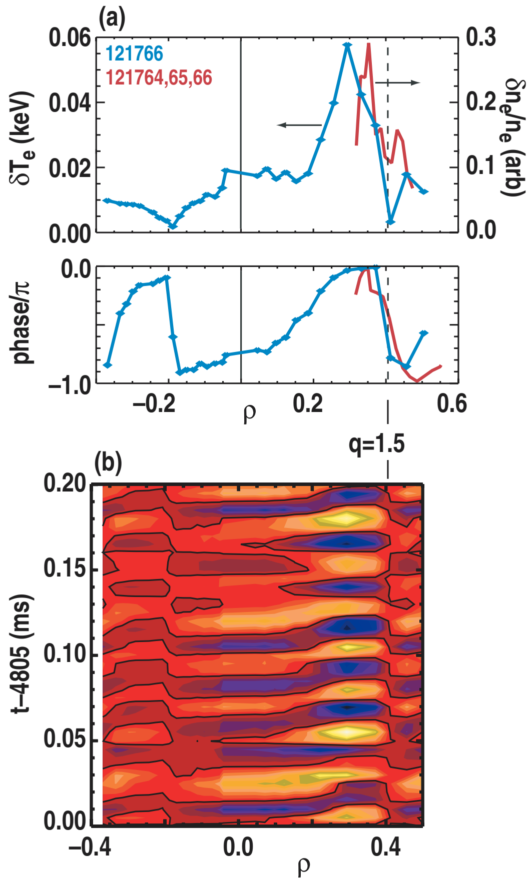

Fig. 3. (a) Amplitude and phase of the electron temperature fluctuations (δT_e, blue) and the relative density fluctuations ($\delta n_e/n_e$, red) versus normalized minor radius ρ associated with the NTM. (b) Contour level plot of δT_e versus ρ and time for an 0.2 ms interval during the stationary period of the discharge. In addition to the dominant m/n=3/2 island at the q=1.5 surface, there is coherent structure near the axis which has the characteristics of the 2/2 spatial sideband.

The experimental connection between the 3/2 mode and the value of q0 is shown in Figure 4. This is the result of an experiment using electron cyclotron current drive (ECCD) localized at the q=1.5 surface to either suppress the 3/2 NTM (with co-ECCD) or enhance the mode (with counter-ECCD). Before application of EC power, the width of the 3/2 island is 0.05 m. These plasmas have q95≈4.1, and so have small sawteeth. When the NTM width is reduced to the noise level, q0 drops by about Δq0≈–0.02; the sawtooth amplitude increases and the frequency decreases. When the island width is increased to 0.085 m, Δq0≈+0.05; the sawtooth amplitude drops and the frequency increases. This dependence of q0 on w3/2 will serve as a test of future nonlinear models of this interaction.

The physics connecting the 3/2 mode and q0 is made by noting that the NTM is a global mode. Although the largest feature is the island chain at the q=1.5 surface, there are m=2, 4, 5, … spatial sidebands, which have a kink-like structure. This is illustrated by linear calculations using PEST3 [10] and NIMROD [11] (Figure 5). In Figure 5a, we have plotted two model cases, with q0=1.008 and q0=1.03. There is no difference in the radial structure of the poloidal harmonics except for the *m=2*. As q0 approaches very close to 1.0, the amplitude of the 2/2 sideband near the axis increases rapidly. This is not unexpected as the q0=1 resonant condition is approached.

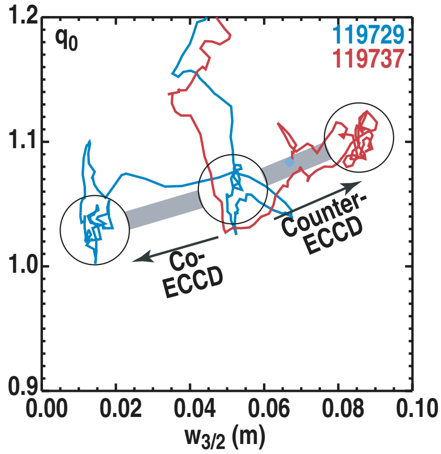

Fig. 4. Time evolution of the central safety factor (q0) and the width of the m/n=3/2 island (w_3/2) for two discharges. In both discharges, initially q(0) decreases toward q0≈1 while the island width remains at ~ 0.055 m. In one discharge (blue) co-ECCD is used to suppress the NTM to the noise level, leading to a reduction of q0 by –0.03. In the other discharge, counter-ECCD is used to increase the width of the 3/2 island, with an increase in q0 of +0.05.

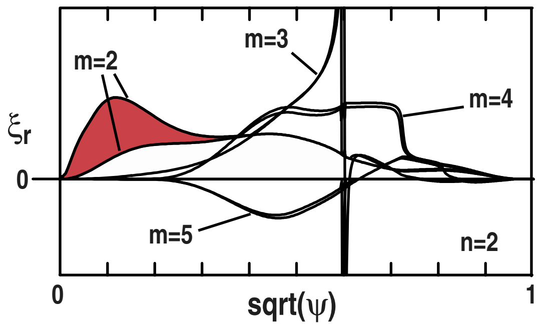

Fig. 5. Mode structure for linear instability. (a) PEST3 calculation of the poloidal harmonics associated with the n=2 toroidal mode, for two values of q0: 1.03 and 1.008. The only significant difference is the increase in amplitude of the m=2 spatial sideband near the magnetic axis for the lower value of q0. (b) linear NIMROD calculation of the perturbed pressure contours. The m=4 sideband can be seen just outside the large m=3 structure, and there is a large m=2 perturbation near the axis.

Physical mechanisms

Another piece of the puzzle is the mechanism whereby the current density at the axis is regulated. Several possibilities are associated with the 2/2 sideband of the 3/2 NTM: there may be a direct current drive associated with this perturbation, or the presence of a helical field perturbation near the axis increases the parallel resistivity (reducing the Ohmic current) and increases radial transport, particularly of fast ions (reducing the neutral beam current drive). To look for an effect on the radial transport of fast ions, we have looked at the neutron rate. A sudden change in the fast ion distribution should be reflected in a sudden change in neutron production, but no such effect is seen. This, if the beam-driven current is being modified, the effect is localized and thus not detectible in the neutron production. Another proposed mechanism under study is the transport of poloidal flux out of the central region because of cyclic reconnection of the 3/2 island. We observe that the 3/2 amplitude is modulated by ELMs, with a rapid drop and a slower recovery. This time-asymmetric behavior may lead to flux pumping and reduction of the time-average central current density, in a manner analogous to the sawtooth effect. However, there is no clear association between this mechanism and q0 ≈ 1.

Conclusions

In the DIII-D realization of the hybrid tokamak operating scenario, an *m=3*, *n=2* NTM acts to modify the current profile in a beneficial way. In the core of the plasma, the current density is reduced, raising q0 to just above 1, resulting in elimination of sawteeth (for q95 > 4) or reduction of the sawtooth amplitude to an inconsequential level (for q95 ≈ 4). This eliminates a trigger for the deleterious *m=2*, *n=1* NTM. The regulation of q0 at a level near 1 is a consequence of the resonant behavior of the amplitude of the 2/2 sideband of te 3/2 NTM, which grows rapidly as q0 → 1. Several candidates for the physical process connecting the 2/2 sideband and the current profile have been identified and are being investigated.

Acknowledgements

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