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MAINTAINING THE QUASI-STEADY STATE CENTRAL DENSITY PROFILE IN HYBRID DISCHARGES

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Maintaining the Quasi-Steady State Central Current Density Profile in Hybrid Discharges * TH-W

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Theoretical results and computational modeling are presented for maintaining the quasi-steady state (without sawtoothing) central current density profile in hybrid discharges. A major conclusion of the theory is that presence of the rotating m=3/n=2 magnetic island provides regulation to the current profile to maintain its quasi-stationary state. Without the 3/2 island, the current profile will evolve and peak at the plasma center to excite the sawteeth and degrade plasma performance. The 3/2 island provides 2 essential roles: (1) It excites the 2/2 sideband near the magnetic axis which then converts into the kinetic Alfvén wave (KAW) driving current countering the current peaking effect; (2) It scatters the energetic particles through its magnetic perturbations to reduce the neutral beam injection (NBI) current drive efficiency. In combination, these effects prevent the development of sawteeth. The rotating 3/2 island may be utilized to prevent sawteeth in hybrid discharges in future devices (i.e. ITER) [1].

The Hybrid scenario, with confinement and β improved above those of the baseline ELMy H-mode, is an attractive scenario for ITER [1]. It would allow ITER to operate near the free boundary n=1 stability limit. It has the potential for sustained ignition in ITER. One intriguing feature of this type of discharge in DIII-D as well as in JET is that the central plasma evolves into a quasi-steady state without sawteeth. The central safety factor (q_0) is kept close to 1 apparently by a rotating 3/2 magnetic island. Equilibrium current profile analysis based on MSE and kinetic profiles for currents from NBI, bootstrap, and Ohmic currents has revealed that the central current density is smaller than the sum of these components when the presence of the 3/2 is ignored [2]. The 3/2 island effectively provides a negative current drive.

In this work, we report on the results of investigation on the causal relationship between the 3/2 island and the non-sawtoothing nature of these discharges. We investigated two mechanisms that provide the negative central current drive; both of which rely on the development of a large co-rotating 2/2 sideband excited by the rotating 3/2 island. In the first mechanism, the central q_0 is assumed to develop to a value below the Alfvén resonance at the plasma center, yet above the value which initiates the sawtooth. For the region within the Alfvén resonance, stationary KAWs are excited by the 2/2 sideband. The KAWs, due to their short perpendicular wavelengths, provide an efficient current drive counter to the plasma current within the resonant region. A theory [3] for this mechanism has been developed which shows that the amount of driven current increases quadratically as the size of the 2/2 sideband. In the second mechanism, the magnetic perturbations due to the 3/2 and 2/2 modes are assumed to redistribute the energetic particle population from the NBI. This explanation is similar to that given in Ref. [4], which proposes that toroidal Alfvén eigenmodes (TAEs) excited by the injected energetic beam ions due to low density result in a redistribution of the energetic particles. However, in the higher density hybrid discharges described here, the TAEs are absent. We propose the scattering and redistribution of the energetic KAW particles is due to the 3/2 and 2/2 MHD perturbations.

To evaluate the first KAW mechanism, equilibria from experimental DIII-D discharges are analyzed using the PEST-III tearing mode stability code and the nonlinear 3-D NIMROD MHD code. The 3/2 tearing mode is found to develop a 2/2 sideband with increasing amplitude as q_0 approaches 1, as expected from standard MHD theory. The 2/2 sideband becomes

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resonant near the plasma center and converts its energy efficiently into the KAWs. Shown in Fig. 1 is the mode conversion process. Note that the perturbed electric potential (which is proportional to the plasma displacement perpendicular to the flux surface) changes sign across the mode resonant surface. This feature agrees with the observed phase shift in toroidal angle between the electron temperature perturbations at the plasma center and the 3/2 island [2]. The short wavelength KAW drives current counter to the plasma current. It is especially efficient when the central q_0 value is kept very close to 1.

To evaluate the second mechanism of 3/2 and 2/2 perturbations on the energetic particles, the ONETWO transport code [5] has been employed to simulate the development of the current profile during NBI. It is found that the NBI-induced current profile depends on the anomalous transport assumed for the energetic ions. Both the NFREYA and the NUBEAM packages [6] gave qualitatively similar results. NBI current profile is broadened by the anomalous transport of the energetic ions. The net effect is an apparent counter-current drive inside of the 3/2 island region relative to the outside. The result of this simulation is shown in Fig. 2, in which the NBI driven current I_{beam} and the neutron reaction rate Γ_{DD} are plotted as a function of the anomalous transport coefficients of the energetic ions used in the calculations. Beyond D=1 m^2/s the apparent negative current drive occurs without appreciable drop in neutron reaction rate [2]. The magnitude of the required magnetic perturbation scales with the required anomalous transport.

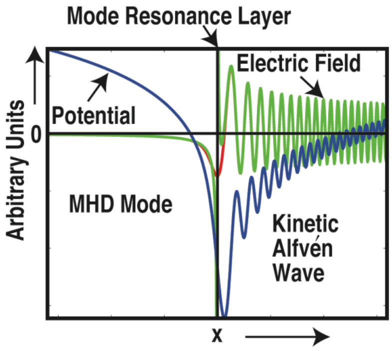

Fig. 1. Conversion of the MHD perturbation (left) into the KAW (right) at the mode resonant surface at $x = 0$. Shown are the electric potential (red) and electric field (blue) and analytic approximation by Airy functions (green).

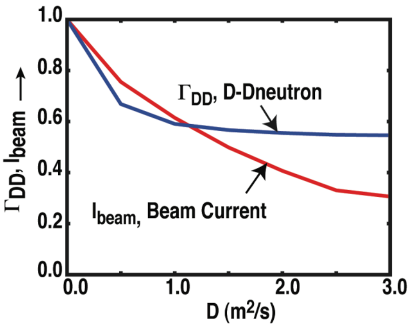

Fig. 2. Relative efficiency of neutral beam current drive and neutron rate as a function of assumed anomalous transport. The nominal anomalous transport, which is needed to match the experimental osbervation, is 1 m^2/s.

The two mechanisms take on complementary roles in these discharges. The mechanism of conversion to the KAW requires q_0 to be very close to 1. A scenario in which the KAW becomes the major mechanism occurs when the q profile is kept near constant in time by the balance between the counter current drive by KAW against the effect of peaking by resistive diffusion. In an alternative scenario, this delicate balance is not maintained. The cyclic oscillation of q_0 dropping below the Alfvén resonance by diffusion and the subsequent action of the KAW mechanism to bring it back above 1 is expected. On the other hand, the mechanism of the scattering of energetic particles by the MHD perturbations depends on the presence of the 3/2 mode. In these discharges, the 3/2 island has been observed to be present throughout. We expect its effect on NBI current drive to be operative throughout. The two mechanisms work in conjunction to prevent the evolution of central q to below 1 and avoid sawteeth.

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