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ADVANCES IN THE PHYSICS UNDERSTANDING OF ELM-SUPPRESSION USING RESONANT MAGNETIC PERTURBATIONS IN DIII-D

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EX-D

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Recent experiments on DIII-D have increased confidence in the ability to suppress edge localized modes (ELMs) using edge-resonant magnetic perturbations (RMPs) in ITER, including an improved physics basis for the edge response to RMPs as well as expansion of RMP ELM suppression to more ITER-like conditions. Experiments aimed at an improved physics understanding have revealed a complex plasma response in the edge region that combines aspects of ideal MHD, vacuum field penetration, and direct turbulent response to the applied RMP. New observations include RMP-induced helical displacements near the separatrix that increase with q_{95} [Fig. 1(a)], a displacement inversion layer in the edge temperature profile response when a rational surface associated with the largest applied RMP poloidal harmonics (m=10-12, n=3 or m=9-11, n=2) is located near the pedestal top [Fig. 1(b)], and nearly instantaneous changes in density fluctuations throughout the pedestal region to n=3 RMP amplitude variations [Fig. 1(c)]. These experiments have taken advantage of DIII-D's unique capability to vary the RMP spectrum (n=3 from one or two internal rows of coils, n=2) as well as toroidal phase variations of n=3 and n=2 RMPs for enhanced diagnostic fidelity, all done at the pedestal collisionality levels expected in ITER. In addition, RMP ELM suppression has been expanded to include the use of n=2 RMPs and has been robustly obtained in the ITER baseline scenario (q_{95}=3.1) using a single-row n=3 RMP.

ELM control is a critical issue for ITER as the anticipated energy pulse associated with unmitigated ELMs is expected to severely limit the lifetime of plasma facing components due to surface erosion. Based on previous DIII-D experiments, magnetic coils internal to the vacuum vessel for this purpose have been included in the ITER design based on specifications derived from DIII-D data. These specifications were based on correlating experimental observations of ELM suppression with vacuum modeling of presumed island generation in the edge plasma. The work described here is aimed at developing a more comprehensive understanding of RMP effects especially in the areas of

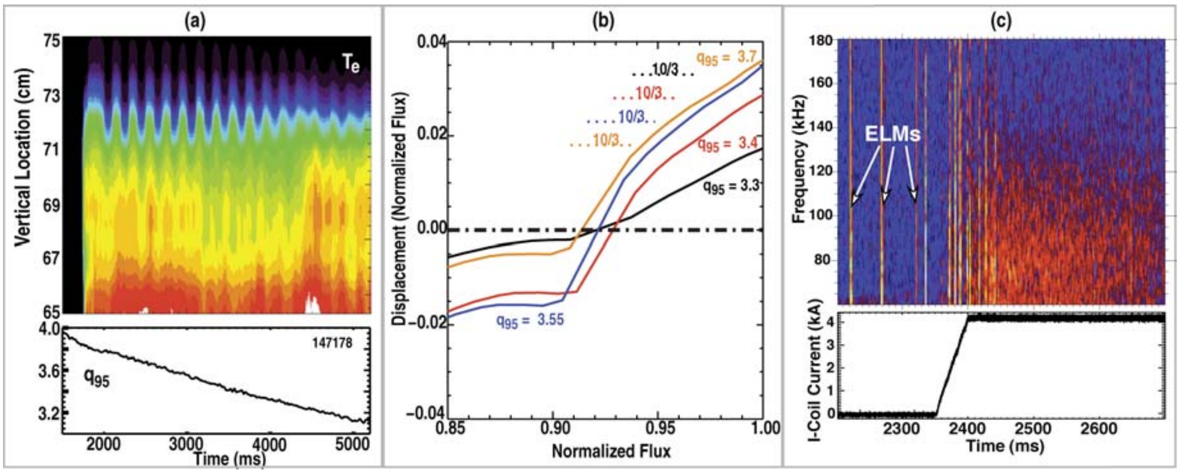

Fig. 1. (a) Temporal and spatial variation of edge temperature T_e profile during n=3 60° toroidal phase modulations of applied RMP; (b) inferred edge T_e radial displacement during n=3 60° toroidal phase shift vs q_{95} compared to location and width of computed m=10, n=3 island (denoted by dotted lines); (c) response of BES-measured density fluctuations near the pedestal top to RMP amplitude turn-on.

kinetic profile response near the resonant window for ELM suppression, magnetic topology response (vacuum vs ideal), and the response of underlying electrostatic turbulence.

Detailed profile analysis of data taken during fine-scale q_{95} scans around the *typical* q_{95} window for ELM suppression ($3.4<q_{95}<3.55$) indicate that while the edge density response is comparable for all q_{95} values, the edge temperature response is much more dependent on q_{95} with the largest variations occurring near the q_{95} window for ELM suppression. The density modifications result in a pressure pedestal width that is approximately 20% smaller than that obtained without the RMP applied. Within the ELM suppression window, the changes in the edge temperature profile result in a pressure pedestal width that is approximately 40% of that obtained without the RMP applied. This modified width is consistent with EPED1 pedestal modeling estimates of the maximum pedestal width before an ELM instability would be expected to occur.

To elucidate the plasma response to the applied RMP, a toroidally rotating $n=2$ RMP and rapid, $n=3$ toroidal phase modulations of the RMP (i.e., a shift of the $n=3$ perturbation by 60^{o}) have been utilized. In both cases, significant displacements of the edge profiles have been observed [Fig. 1(a)]. In the rotating $n=2$ case, the edge displacement as inferred from tangential viewing images of the beam emission spectroscopy (BES) emission is on the order of 2 cm, roughly five times larger than that expected from vacuum modeling estimates of the radial displacement of manifold structures calculated using TRIP3D-MAFOT. The edge displacement, observed on a range of diagnostics – on and off the midplane, extends a few centimeters inside the separatrix at the midplance, increases as q_{95} is increased, and is consistent with a helical deformation of the plasma column. Preliminary M3D-C1 code modeling of the plasma response is qualitiatively consistent with the observations.

Detailed analysis of edge Thomson scattering data electron temperature during the $n=3$ toroidal phase modulations have revealed that at q_{95} values in which complete ELM suppression occurs, this helical deformation [Fig 1(b), $\psi_N>0.95$] is accompanied by an inward displacement just inside this region. The location of the associated inversion layer moves radially inward as q_{95} is increased and is roughly coincident with SURFMN vacuum calculations of the expected location of the $m=10$, $n=3$ island. Furthermore, the magnitude of the inward displacement is quantitatively consistent with the computed size of the $m=10$, $n=3$ island. These observations are consistent with a recent theory that island formation may inhibit growth of the pedestal width to allow stable operation below the peeling-ballooning stability limit. It is important to note that the location of the island in these cases is near the top of the pedestal, not in the high pressure gradient region, allowing the possibility of a small electron perpedicular velocity and hence penetration of the RMP fields to the rational surfaces in this region. While the observations are consistent with expectations if an island is present, this data set is insufficient to discriminate between an island-like displacement and a kink-like displacement at the very edge accompanied by a global change of transport inside the pedestal region. Future experiments will seek to address this issue.

Measurements using BES, DBS, and high-k backscattering consistently show increases in the fluctuation level with RMP amplitude, which is relatively independent of q_{95}. For the case of low-k fluctuations measured by BES, the time scale of the response of turbulence is comparable to the time scale of the RMP amplitude variation. This response time is faster than that of the underlying density and rotation profiles, suggesting a direct impact of RMPs on turbulence.

Finally, RMP ELM suppression has recently been demonstrated in the ITER baseline scenario with $q_{95}=3.1$, $\beta_N\sim1.8$, $H_{98}\sim1$, enabled by use of a single internal row, $n=3$ RMP (Fig. 2). Although ELMs correlated with internal $n=1$ activity are observed, full ELM suppression is sustained for >1 s once this activity dissipates. Similar durations of ELM suppression with $n=2$ RMP perturbations have also been obtained. Such capability has allowed probing of the full toroidal response of the edge profiles through continuous rotation of the $n=2$ perturbation.

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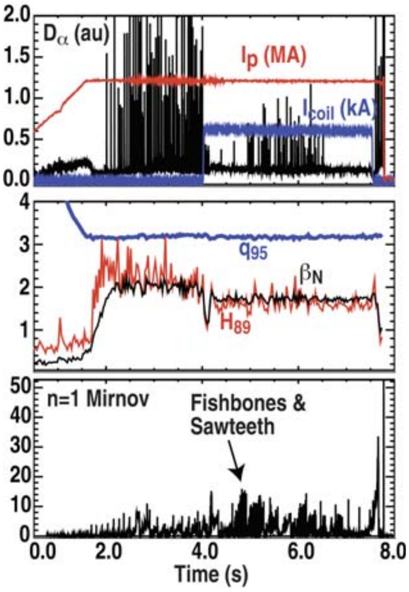

Fig. 2. Selected waveforms from DIII-D discharge demonstrating RMP ELM suppression in the ITER baseline scenario with $q_{95}=3.1$.