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TRANSPORT AND MHD ANALYSIS OF ELM SUPPRESSION IN DIII-D HYBRID PLASMAS USING *n*=3 RESONANT MAGNETIC PERTURBATIONS

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Recent experiments on DIII-D have extended edge localized mode (ELM) suppression using n=3 resonant magnetic perturbations (RMPs) [1] to the hybrid regime with β_N=2.5 (β=3.4%) [2,3]. In this regime with strong co-neutral beam injection, the application of the RMP leads to a 20% reduction in energy confinement; however, $H_{98y2} > 1$ is maintained. This reduction in confinement is due to both a reduction in the core rotational shear as a result of coupling between the RMP and an existing m=3, n=2 neoclassical tearing mode and a modest decrease in the pedestal height. The enhanced drag between the RMP and neoclassical tearing modes (NTMs) leads to a factor of three reduction in the momentum confinement time; the reduction in the pedestal toroidal rotation limits the duration of RMP ELM suppression and in some cases results in locked modes. The measured pedestal height during the RMP is found to be slightly lower than predicted by the EPED1 model [4], suggesting that the RMP modifies the underlying transport in a manner not captured by this model. Further analysis indicates that the observed ELM suppression is consistent with previous findings that the RMP reduces the edge pressure gradient sufficiently that the operating point moves into a stable regime.

The hybrid regime is extensively studied in DIII-D in support of the ITER mission. Hybrid plasmas are characterized by excellent confinement, H_{98y2}>1, and the ability to operate at β_N>2.5. Hybrid plasmas in DIII-D are characterized by a small m=3, n=2 NTM which leads to suppressed or reduced amplitude sawteeth [5], although occasionally a 4/3 NTM is dominant. The ELM suppression by RMP on DIII-D lasts for ~1 s (about 0.5 times the current redistribution time), as shown in Fig. 1. The growth of a 3/2 NTM and the resulting drag from the interaction with the RMP fields [6] results in the return of ELMs at t = 3500 ms when the pedestal rotation decreases to ~40 km s^{-1}, as seen previously with co/counter-NBI plasmas. Energy confinement decreases from H_{98y2}=1.35 to H_{98y2}=1.05 during the RMP phase as a result of the small decrease in toroidal rotation as well as the large change in plasma temperature and density profiles.

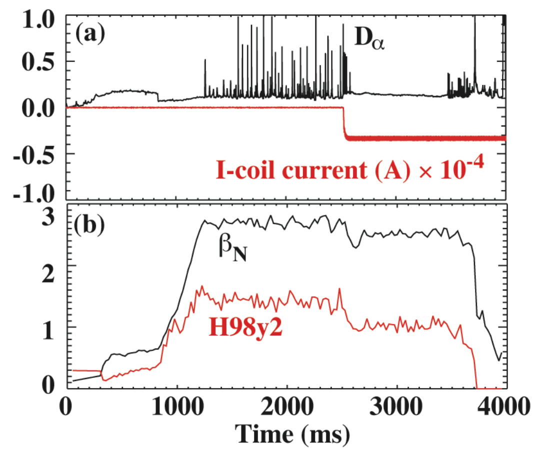

Fig. 1. ELM suppression in a hybrid discharge (a) D_α (black) and I-coil current (red) (b) β_N (black) and confinement (H_{98y2} scaling) (red).

The experimentally measured pressure pedestal gradient [Fig. 2(a)] and the neoclassical edge current [Fig. 2(b)] gradient, calculated with the Sauter bootstrap current model, are reduced during RMP. Comparison of the measured pedestal height with the EPED1 model indicates that EPED1 overestimates the pedestal height by 10%-30% when the RMP is applied. Since the EPED1 model [7] has successfully been used to predict the total pedestal height in standard ELMing H-mode discharges across a number of different machines, this disagreement suggests that the present pedestal models need to incorporate an additional loss channel to account for energy transport during RMP. If small ELMs are present, the agreement between the model and the experiment improves. This may occur because of stochastic transport induced by RMP in the resonant window, which is not included in the EPED1 model.

An important aspect of the transport in the edge is the details of the magnetic topology. Detailed studies indicate that the inclusion of the edge bootstrap current can strongly affect the zeroth order field line trajectories, as well as the interaction of proximate edge magnetic resonances. Figure 2(c) shows the effect of including the bootstrap current on the q-profile, while keeping the total plasma current constant. In the edge, the current modifies the local magnetic field and distorts the q-profile from a smooth monotonically increasing function. This distortion leads to a reduction of the calculated field line stochasticity, which is a typical metric for the design of RMP coils and RMP experiments. By utilizing the field line tracing code, it was calculated that the magnetic diffusion in the pedestal was reduced by around 30% relative to a discharge time when the edge current was a factor of two lower.

The edge stability to peeling-ballooning (P-B) instabilities in these DIII-D hybrid plasmas has been calculated using the ELITE code. ELITE calculates the stability of intermediate toroidal mode number modes, $3<n<10$, as a function of the pressure gradient and current gradient. For the analyzed hybrid discharges within the "resonance window" of q_{95} (3.6±0.2), the lack of large Type-I ELMs during RMP is consistent with the predictions of the ELITE code that the pedestal region is P-B stable. When outside the resonant window in q_{95}, high-frequency, low-amplitude ELMs appear during RMP. The ELITE code calculates these plasmas are still stable to P-B modes, suggesting that these smaller ELMs are not Type-I and their study may point the way to understanding the physics of the RMP q_{95} resonance window.

This work has shown that the hybrid scenario, a leading scenario for ITER baseline operation, is capable of complete ELM suppression as in standard H-mode discharges and that our understanding of the physics of RMP ELM suppression applies to hybrids.

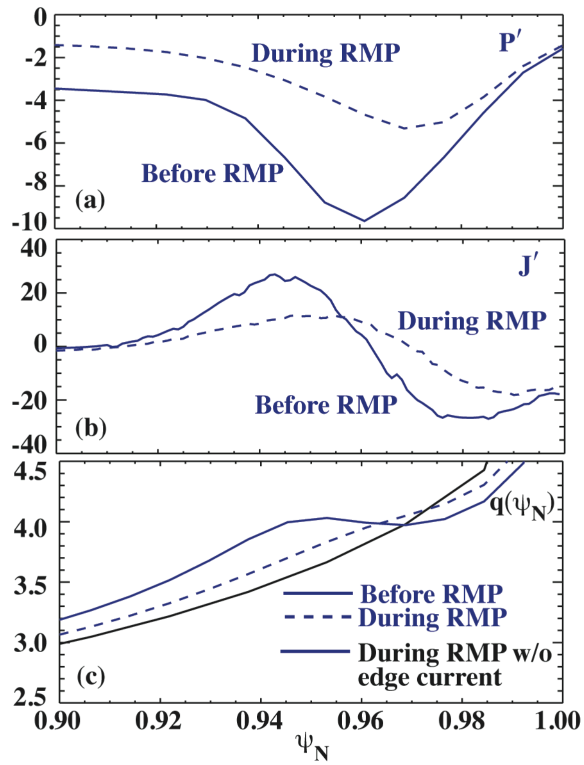

Fig. 2. Edge gradients before (solid line) and during (dashed line) RMP. Pedestal pressure gradient (a) and current density gradient (b) show reduction due to increased transport. (c) Current reduction is reflected in the safety factor, q, profile. Comparison with a model neglecting the edge current density is shown (dash-dot).

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