Improved Particle Confinement with 3D Magnetic Perturbations in DIII-D H-mode Plasmas

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Experiments on DIII-D have identified a robust regime in which applied 3D fields increase the particle confinement and overall performance while partially stabilizing the peeling, edge-localized modes (ELMs). Controlling ELMs using resonant magnetic perturbations (RMPs) is the leading strategy for preserving reactor first wall components from destructive heat fluxes, but the 3D fields used have hitherto been observed to degrade the particle confinement via the density “pump-out” phenomenon. Recent DIII-D experiments show that there is a range of counter-current rotation over which 3D fields instead increase the particle confinement and stabilize certain edge peeling modes in H-mode plasmas (figures 1 and 2). This density “pump-in” has the potential to minimize or even reverse the confinement degradation cost currently expected in RMP reactor scenarios.

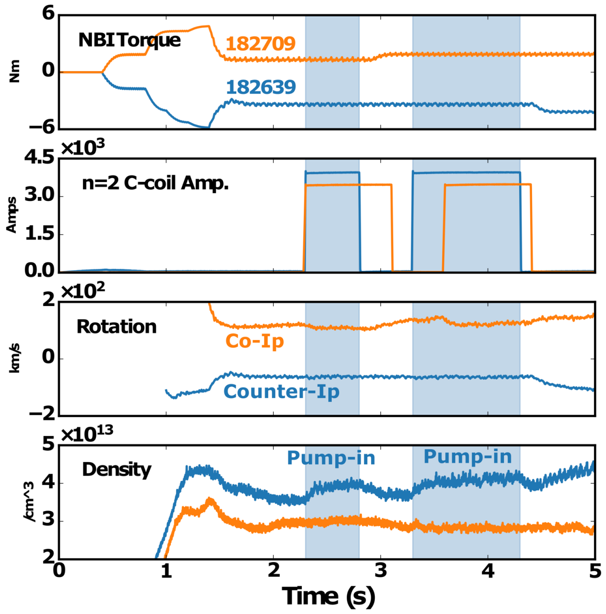

Figure 1: With constant NBI torque (top), the application of n=2 3D fields (second) in a discharge rotating opposite Ip (third, blue) causes a rise in plasma density (bottom).

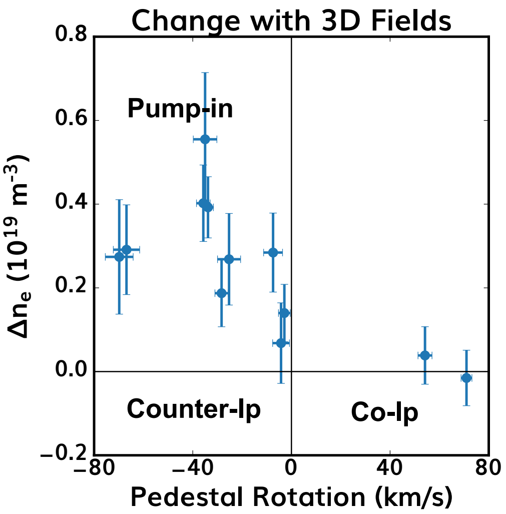

Figure 2: Increase in line integrated density observed when 3D fields are applied across a broad range of pedestal-top rotations.

The application of n=2 3D fields consistently and robustly caused the density to rise in ELMing H-mode, reverse Ip, upper single null discharges across a range of moderate counter-Ip rotations (figure 2). The effect disappears near zero rotation and is not observed in “normal” plasma current (Ip) plasmas (figure 1, orange). The extensive suite of edge and plasma material interaction diagnostics of DIII-D do not detect any changes in the wall particle source associated with the 3D fields responsible for the observed rise in density. While the ELM frequency changes when 3D fields are applied, ELM-synchronized measurements of the pedestal density evolution indicate that the net change in ELM induced particle flux is not sufficient to explain the change in total density observed. The pump-in plasmas have finite co-directional E×B and electron diamagnetic precession frequencies (ω_E and ω_{*e} respectively) from the pedestal top to bottom, shielding islands and providing no inward resonant transport across rational surfaces (which would require $\omega_E/\omega_{*e} < -1$ in resistive MHD [1]). The 3.5-4kA RMP from DIII-D's midplane "C-coil" array is a mix of resonant and non-resonant magnetic perturbations and below any ELM suppression threshold that may exist in these scenarios. Thus, we conclude the 3D fields are modifying fundamental confinement physics in the pedestal of these plasmas and that this physics is distinct from the resonant island physics thought to be responsible for ELM suppression [2,3].

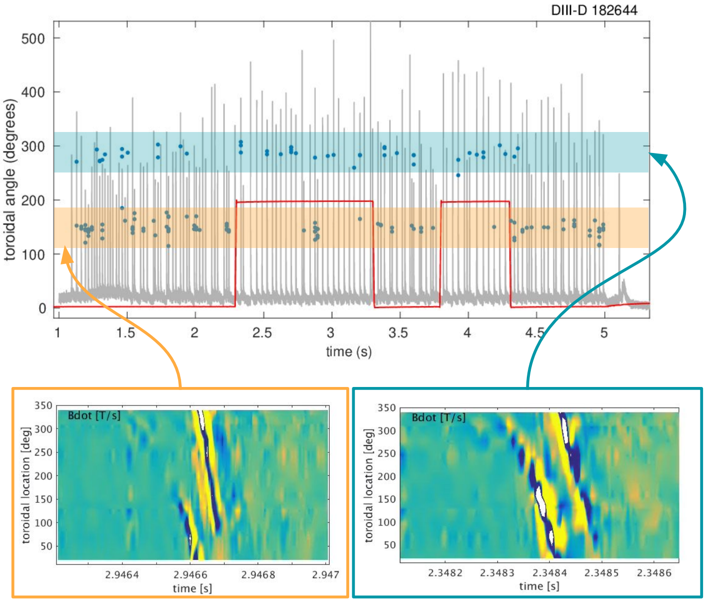

Figure 3: ELMs (top, grey, arb. units) identified by fast 3D magnetic sensors (bottom) as originating near 120° toroidally around the machine are stabilized by the application of 3D fields (top, red, arb. units).

Generalized Perturbed Equilibrium Code (GPEC) calculations show the neoclassical non-ambipolar ion transport in the pedestal region is qualitatively consistent with the observed changes in the particle confinement. The inward neoclassical ion flux is on the order of 3×10^{18} $m^{-2}s^{-1}$ for plasmas with the largest density pump-in. Mitigated turbulent fluctuations are also observed coincident with the applied fields, corresponding to reduced outward turbulent fluxes. These transport mechanisms change the particle confinement in ways independent of the resonant island physics governing ELM suppression.

While changes in ELM dynamics do not dominate the observed pump-in, it is notable that the reduced ELM frequency and increased ELM size with applied fields is the opposite of the pervasive RMP ELM mitigation behavior (smaller, higher frequency ELMs) observed internationally on tokamak RMP experiments. This novel observation implies the 3D fields are partially stabilizing certain edge peeling modes (identified as such using ELITE, which shows no change in the axisymmetric boundary in current and pressure). Measurements from a toroidal array of Mirnov probes show ELMs are only born at two particular toroidal angles without applied 3D fields and only one location with the n=2 3D fields applied (figure 3). This suggests that a peaking of multi-n intrinsic error fields destabilizes the ELMs at a specific location and that this ELM-causing EF can be "corrected" with low n 3D fields coils.

New DIII-D experiments have found and detailed a new regime in which 3D fields like those planned to suppress ELMs in future reactors increase the particle confinement and stabilize certain edge peeling modes. These effects are distinct from the resonant island physics thought to cause full suppression of the ELMs. These findings introduce a new path for understanding the impact of 3D fields on particle confinement and minimizing the degradation of plasma performance in the reactor scenarios using 3D fields.

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