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Plasma Response to Applied Resonant Magnetic Perturbations in DIII-D

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Resonant magnetic perturbations (RMPs) have been applied to tokamak plasmas as a means of controlling [1] edge localized modes (ELMs), in an effort to mitigate the deleterious effects of these impulsive heat loads on future tokamak devices [2]. In DIII-D, the application of n=3 RMP fields induces a reduction in the edge pressure gradients [3,4] thereby suppressing Peeling-Ballooning modes [5] and therefore, ELMs [6]. On the other hand, ELM mitigation was achieved in JET with a n=1 RMP field that resulted in reduced ELM size and increased ELM frequency [7]. Application of a n=3 RMP in DIII-D reduces the edge pressure gradient by lowering the electron density, ne, which dominates over an increase in the ion temperature, Ti. In contrast, application of a n=3 RMP in NSTX produces a local increase in electron temperature, Te, and no change in ne, triggering ELMs, instead of suppressing them, by pushing the pressure gradient above the peeling-ballooning threshold [8]. The observed changes in the Te, ne, and Ti profiles, vary significantly depending on the periodicity of the RMP used (n=1, 2, or 3), plasma collisionality, ν_e^*, and plasma confinement mode, etc., but eventually, they are ascribed to particle and heat transport modification [9] caused by yet unidentified physics. There are various conceptual models on how magnetic islands or stochastic layers can affect particle and heat transport [1], but even more fundamental issues about island formation need to be resolved given plasma shielding or even amplification of the applied magnetic fields by plasma rotation and plasma response in the form of local currents as theory [10] predicts. In short, it is unknown how the vacuum predictions reflect the true topology of the plasma-RMP system.

In order to tackle some of these fundamental questions, coils are programmed to produce what vacuum modeling predicts to be magnetic islands n/m=1/3 of large radial size (~1-2 cm) were created in the boundary region of inner column-limited ohmic plasmas with plasma current, I_p ~ 1.3 MA and B_T = 2 T, in the DIII-D[1] tokamak. The islands were shifted in location, by changing the phase of the coil currents, to place them in front of the diagnostics. They were also changed in size, by changing the current amplitude of the external coils inducing them, as shown in Fig. 1. We first compared the X and O points of islands at I_c = 1 kA [Figs. 1(a,b)] and then increase I_c to 3 kA, which results in an island radial extent to ~2.2 cm or ψ_n = 0.4–0.7 in normalized flux coordinates.

The main diagnostic used for this work is a fast scanning probe with five tips. It is located 18 cm below the outer midplane and penetrates ~4-5 cm into the core. The probe has a radial resolution of ~1.5 mm and most quantities are measured with a bandwidth of 500 kHz. The sampling of the island's O and X point was performed to: 1) show that the islands affect the local plasma, 2) reveal any 2D and 3D structure and 3) try to provide a physical mechanism for the observed profile changes.

The data obtained from the scanning probe array is shown in Fig. 2(a-f), where the LCFS determined from EFIT is marked with a vertical dashed line. The expected island width and location, as per TRIP3D vacuum calculations are marked with a shaded vertical band. The profiles of plasma potential (calculated as $V_f + 2.5\ T_e$), T_e and n_e are shown in Figs. 2(a-c). They are different for the X point and O point locations, immediately indicating: 1) the applied perturbation changes the local plasma, 2) the perturbation is a 3D structure, and 3) the profile changes extend into the scrape-off layer (SOL).

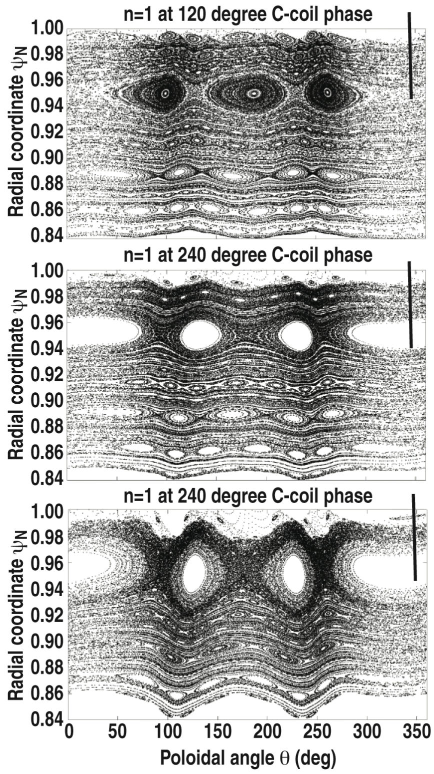

Fig. 1. Vacuum calculations of the magnetic topology using the code TRIP3D [11] for three n/m=1/3 configurations, the probe is shown as a quasi-vertical line: a) a 1 kA C-coil case with a X-point in front of the probe, b) same with O-point in front of the probe and c) C-coil current increased to 3 kA to open the island.

Information on particle transport is shown in Fig. 2(d-f). In particular, the poloidal electric field, E_θ, shown in Fig. 2(d), is sensitive to the applied I-coil current and phase (corresponding to vacuum modeling island structure and radial island size). Both radial and poloidal electric fields are routinely measured with probes and compared to other diagnostics, such as charge exchange recombination spectroscopy (CER, CHERS). The field changes dramatically when sampled at the O or X point and it changes sign inside the O-point for the highest coil current. This field results in a radial flux from $\Gamma_r^{DC} = n_e E_\theta / B_\phi$ that reaches ~10^{21} $cm^{-2}s^{-1}$ locally and provides a first mechanism for radial transport modulation by RPMs. This local particle flux is sufficient to account for more than the whole particle inventory, and it must be noticed that the flux can be inward or almost null locally depending on spatial location and the magnitude of the I-coil current. Finally, Fig. 2(f), showing the turbulent radial particle flux, $\tilde{\Gamma}_r = \langle \tilde{n}_e \tilde{E}_\theta \rangle / B_\phi$, provides evidence for a second RMP- modulated transport mechanism since the flux shifts radially inside the plasma at the O point locations and increases in strength by a factor of 2. Another notable fact is that although the n_e and T_e profiles do not seem to clearly delineate the islands, the E_θ profiles do so by quickly diverging inside the $\psi_n \sim 0.97$ location.

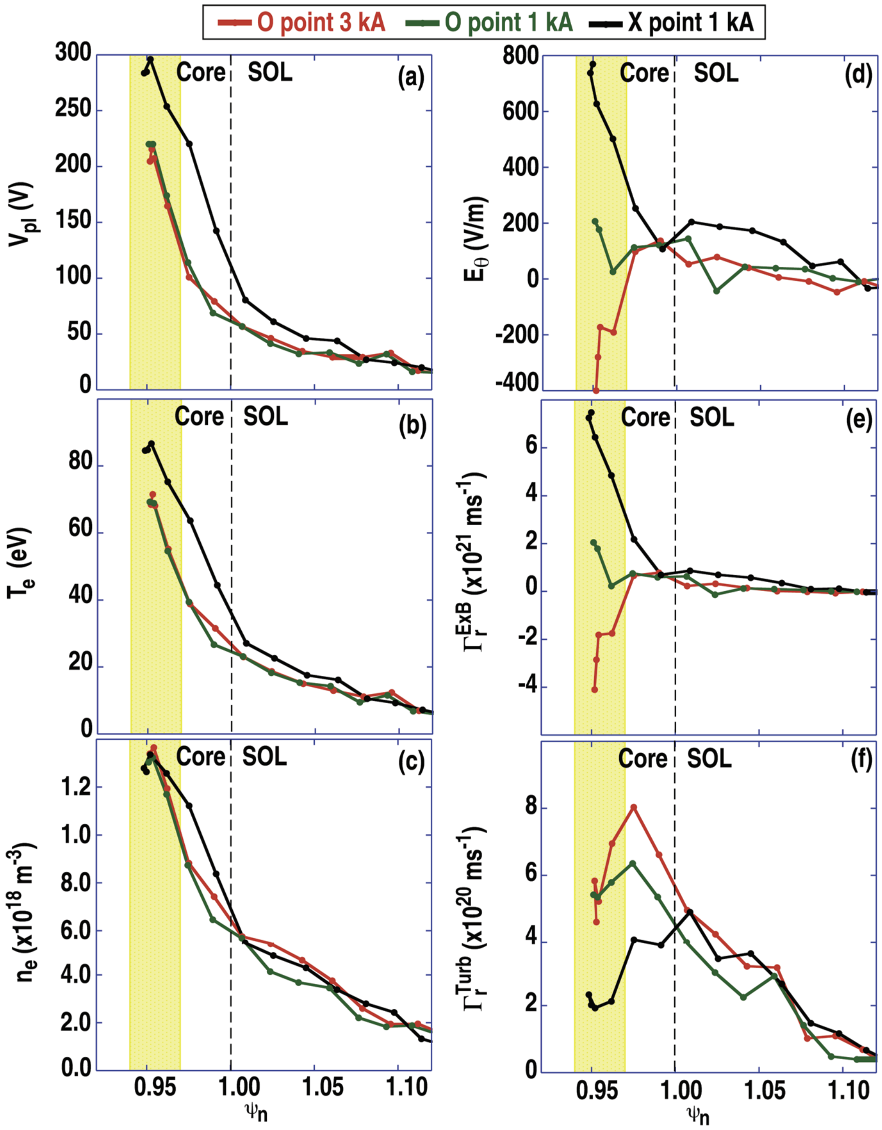

Fig. 2. Data from the midplane scanning probe showing profiles of: (a) Plasma potential, (b) electron temperature, (c) electron density, (d) poloidal electric field, (e) $E \times B$ flux from the previous field and f) turbulent radial particle transport from fluctuations. The profiles are plotted vs. poloidal normalized flux. The expected island location, as TRIP3D modeling is shown as a shaded box and the position of the LCFS is indicated by a vertical dashed line.

The conclusions from this data are: 1) the application of an external 3D magnetic field creates a 3D structure in the plasma, 2) a poloidal electric field is formed that varies radially and provides a clear mechanism for local transport, and 3) changes in the radial turbulent transport provide a second transport mechanism to support global discharge modifications.

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