Measurements of the Perturbed Rotation in Slowly Rotating Tearing Mode Islands in DIII-D*

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Introduction

Neoclassical tearing modes (NTM) are instabilities which are destabilized and maintained by helical perturbations to the pressure-gradient driven "bootstrap" current. The resulting magnetic islands break up the magnetic surfaces that confine the plasma. The NTM is linearly stable but nonlinearly unstable, and generally requires a "seed" to destabilize a metastable state. In addition, a rotating m/n=2/1 and/or 3/1 island induces eddy currents in the resistive wall that create drag that can bring the island (and plasma) rotation to a stop . This can lead to loss of H-mode and a disruption. A key feature for small island onset is how the ion flow is perturbed by the island. A helically modified ion flow leads to helical ion polarization currents which can either be stabilizing or destabilizing according to both the sign and magnitude of the perturbed flow [1] and [2]. Measuring the local phase shift (if any) and the radial structure at the island of the perturbed flow, with respect to the perturbed magnetic field, is a key measurement to sort out the nature of the ion polarization current [3].

Measuring the Perturbed Radial Profiles in Freely Rotating Islands

The n=1 island structure is measured with electron cyclotron emission (ECE) radiometry. The ion rotation and temperature are measured by the fastest possible resolution (274 μs) charge exchange recombination (CER) spectroscopy. A slowly rotating island is needed with a long period of near constant rotation and plasma parameters. This allows the CER diagnostic to resolve the island temporal variation. Coupled m=(1,2,3,4), n=1 modes are slowed down to 1 kHz (max allowed for CER resolution) by near balanced beams. To prevent locking to the wall, the q=2 and q=3 surfaces were placed at smaller normalized radius ρ than usual by setting $q_{95} = 8$; this reduces wall coupling. $\beta_N \simeq 1.8$ ($\beta_\theta \simeq 1.4$) so that the mode was also not large enough for locking. However, the islands were still large enough for the radial resolution of the CER and ECE diagnostics. To get both tangential and vertical rotation data, two different discharges were compared with the 30L neutral beam swapped with the 330L neutral beam to get both the tangential and vertical CER chords. The frequency of the island in the interval of interest is that at which the FFT amplitude of the fluctuating field, measured by Mirnov coils, was at a maximum. Each of the ECE and CER data channels had a linear offset removed and then was fit to a cosine with the frequency fixed to the island frequency and the amplitude and phase as free parameters. After correcting for the expected phase shift in the n=1 signals due to the different toroidal positions of the diagnostics, the complete radial profile of the perturbed quantities with respect to the island can be determined. The resulting perturbed temperature and rotation measurements are shown in Fig. 1. It can be seen that the perturbed T_i profiles agree with the perturbed T_e profiles. The zero crossings and local extrema in the perturbed temperature profiles show the location and size of the islands. The measured perturbed rotation has a local extremum at the island O-points with oppositely oriented extrema located just outside the island.

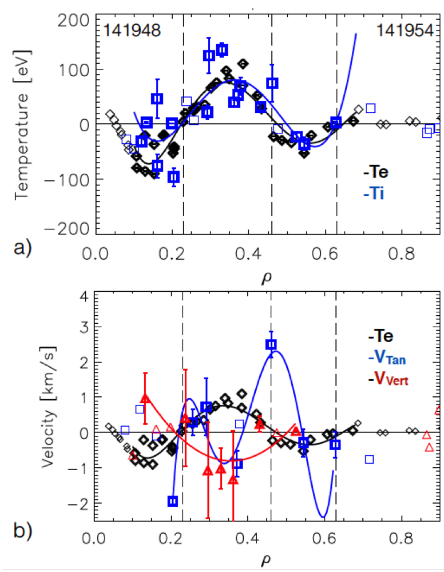

Figure 1: *a) Measured perturbed temperature for 1 kHz island. Dashed lines are q=2,3,4. b) Measured perturbed rotation. Local extrema observed at the location of the island O-point/X-point.*

The perturbed radial profiles of T_e, T_i and rotation near the q=3 surface (location where the best resolved perturbed rotation signal was the largest) were fit to polynomials. The order of the polynomial for each profile was determined by minimizing the reduced χ^2. Only data points that had an uncertainty in the phase angle less than 15° from the cosine fitting were included in the polynomial fits. By taking both the phase and amplitude information from the cosine fits, a radial profile for each of the perturbed quantities was determined over an entire island rotation period. The structure of the perturbed rotation profile near a slowly rotating n=1 tearing mode island over two periods is shown in Fig. 2.

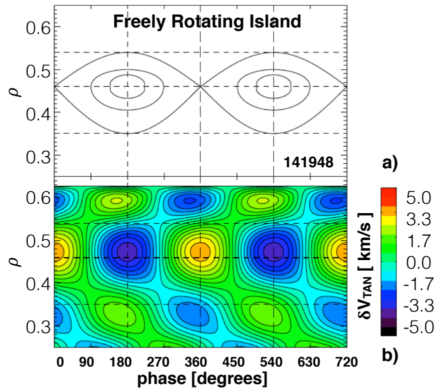

Figure 2: *a) Reconstruction showing the location, size and phase of the m/n=3/1 island, determined by the Te profile. b) The perturbed toroidal rotation near the q=3 surface for two periods. Rotation extrema at the rational surface are in phase with the island.*

The perturbed toroidal rotation is toroidally in phase with the island and has a local minimum at the island rational surface at the O-point. The perturbed rotation also has local maxima located radially just outside the island. The perturbed vertical rotation was relatively small and there was not enough spatial resolution to make any definitive statement on its radial structure. The measured perturbed rotation described above qualitatively agrees with the theoretical picture presented by [1] and [2].

Measuring the Perturbed Radial Profiles in Entrained Rotating Islands

An alternate method to producing a slowly rotating n=1 island structure is to allow it to lock and be entrained by a 10 Hz rotating applied field from the “I-coils" [4]. This puts the rotation in the standard 5 ms CER resolution, but the physics of entrained islands may differ from that of freely rotating ones. Here, $q_{95} = 4.8$, $\beta_N = 1.3$ (as L-mode) and $\beta_\theta = 0.65$, with the q=2 surface at a more typical (larger) $\rho = 0.57$. As a result, the entrained n=1 island structure includes only m=1 and 2. Figure 3 shows the 10 Hz perturbed temperature and rotation profiles.

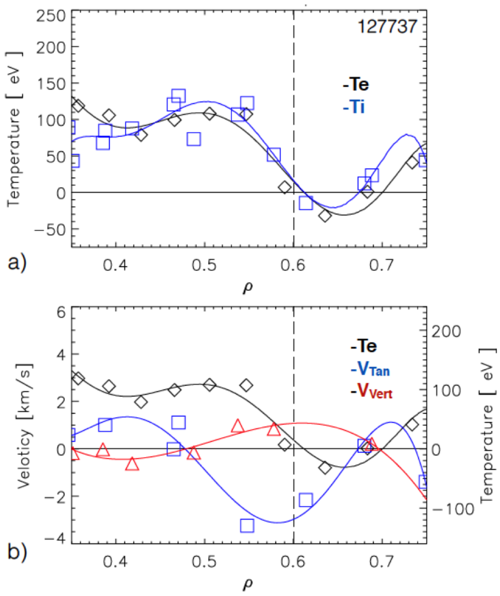

Figure 3: *a) Measured perturbed temperature for 10 Hz island. Dashed line is q=2. b) Measured perturbed rotation. Local extrema observed at the location of the island O-point/X-point.*

As in the freely rotating island case (m/n = 3/1 at 1000 Hz), the perturbed 10 Hz entrained case ion temperature profile agrees with the perturbed T_e profile and shows the location and size of the island. The perturbed rotation profile island has extrema at the island O and X-points, as shown in Fig. 4, with opposite sign extrema in the “wings.” The perturbed poloidal rotation is much smaller than the toroidal rotation, but it is also peaked near the q=2 rational surface and in phase with the island O and X-points.

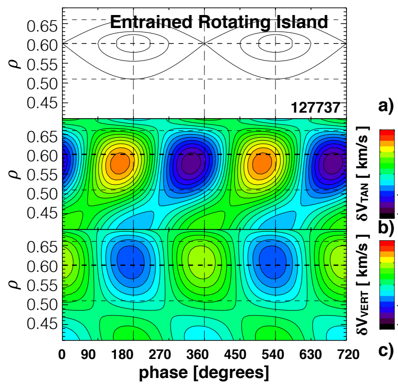

Figure 4: *a) Reconstruction showing the location, size and phase of the m/n=2/1 island, determined by the Te profile. b) The perturbed toroidal rotation near the q=2 surface. c) The perturbed poloidal rotation. the rotation is peaked at the rational surface and in phase with the Island.*

M3D-C1 Code Comparison for Freely Rotating Island Measurements

M3D-C1 allows us to compare the measured, saturated, non-linear perturbed rotation in the experiment with the linearly perturbed rotation in an MHD simulation [5]. Given the equilibrium profiles from the DIII-D case with the freely rotating 3/1 island, an M3D-C1 simulation found multiple linearly unstable (n=1, m=2,3,4,5) tearing modes present, the most unstable being a 5/1 mode.

Shown in Fig. 5 are contours of the linearly perturbed poloidal magnetic field and toroidal rotation along the lower-field side midplane. The toroidal rotation appears to be peaked at each of the rational surfaces and 90° out of phase with the tearing modes. The difference in relative phase from the experimental measurements may be due to the non-linear torque of the island on the rotation.

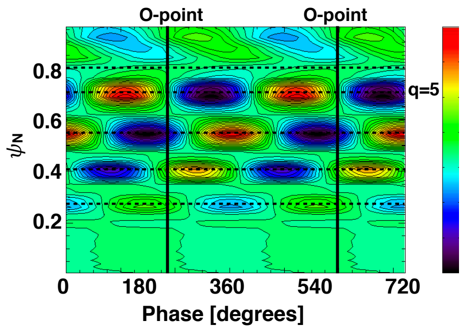

Figure 5: *The n=1 perturbed toroidal rotation from a M3D-C1 simulation. Dotted lines indicate the location of the q=2,3,4,5 and 6 surfaces. The solid lines indicate the phase of the O-point for the 5/1 mode*

Conclusions

A helically modified ion flow can lead to helical ion polarization currents which can either be stabilizing or destabilizing according to both the sign and magnitude of the perturbed flow. In the freely rotating case presented here the measured perturbed flow was in phase with the island O-point and the inferred ion current ($\delta j = \sum n_i Z_i e V_i$) was about 1/3 the magnitude and in the same direction as the estimated island q=3 helical current density. However, for the entrained case, the inferred ion current, while also peaked on the island rational surface, is both smaller ($\sim$ 1/10) and in the opposite relative sign. These measurements had to be done for large saturated islands in which diagnostic radial resolution was good enough for the island structure. The M3D-C1 code comparison is for the linear "small island" non-saturated evaluation while NTM thresholds from helical ion polarization current theory are only developed for small islands of significance at onset of growth. However, those measurements should be a basis for testing threshold theory physics.

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