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The Single Dominant Mode Picture of Non-Axisymmetric Field Sensitivity and Its Implications for ITER Geometric Tolerances EX-S

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Experiments at DIII-D have demonstrated that several key 3D field sensitivities are directly related to their coupling to the least-stable kink mode of the plasma, and concomitantly that the plasma is remarkably insensitive to fields which have no net coupling to this single dominant (kink) mode. Specifically, plasma rotation and error field (EF) penetration thresholds are nearly unchanged despite application of large amplitude n=1 probing fields with no kink coupling, as shown in Fig 1. The plasma sensitivity to 3D fields which have no kink coupling is of critical importance as this sets the true geometric tolerance of the tokamak — so long as it is equipped with at least a single row of EF correction coils (EFCCs) and its 3D field sources are well characterized, thus allowing the kink-coupling of the intrinsic EF to be nulled by the EFCCs at each controllable n. The observed weak sensitivity to the no kink coupling field challenges the stringent tolerance requirements currently enforced [1], as a strong performance recovery when using EFCCs is expected though it is not presently taken into account.

The validity of the single dominant mode picture [2] is determined experimentally by contrasting the plasma sensitivity to large-amplitude probing fields that have varying levels of coupling to the kink mode [3]. The single dominant mode picture is strongly obeyed for each scenario tested, with very small kink-orthogonal sensitivities found. Note the kink mode coupling of the n=1 probing field can be nulled by using two EFCC sets, and examples using various combinations are presented. Sensitivity to rotation braking is contrasted in both H- and L-mode plasmas, shown in Fig. 1(a,b). For both scenarios, braking by the probing field is reduced by nearly a factor of ten when the kink mode coupling is nulled. EF penetration is also contrasted with both H-mode and Ohmic plasmas. Penetration is triggered in the Ohmic

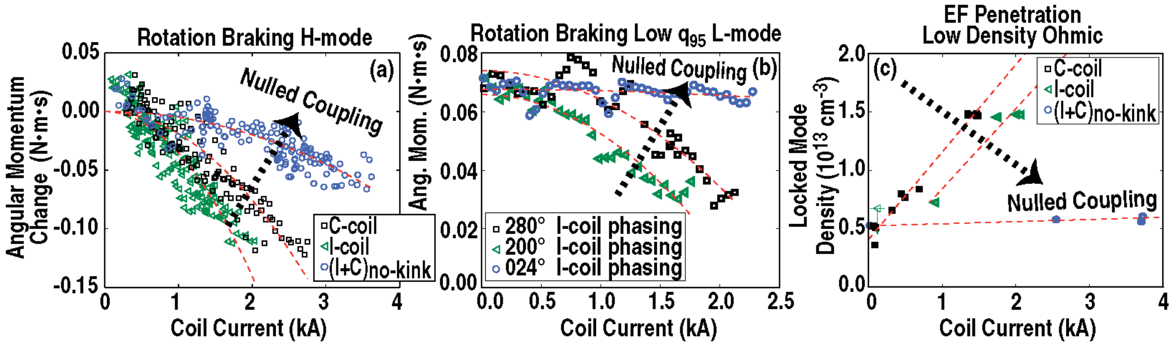

Fig. 1. Comparison of sensitivity to n=1 probing fields for various scenarios as coupling to the single dominant mode is nulled. Nulled coupling is achieved experimentally by using one EFCC set to null the kink coupling of a second set. Examples using in-vessel only as well as in- and ex-vessel combinations are presented.

plasma [shown in Fig. 1(c)] by ramping the EFCC current, while in the H-mode plasma (not shown) the injected torque is ramped down. In both, the penetration threshold is nearly unchanged (vs a no-field baseline) when the probing field has no kink coupling, despite its large amplitude.

The maintenance of the edge rotation due to the neoclassical toroidal viscosity (NTV) with n=2 fields is also largest when coupling to the kink is maximized. Experiments are performed in counter-rotating plasmas near kinetic resonances of the NTV torque, allowing isolation of the NTV effect (counter-directed) from standard resonant braking (co-directed). This is in contrast to the usual co-rotating regime, where both the NTV and resonant mechanisms result in braking [4]. Figure 2 illustrates the observed changes in the NTV (again vs a no-field case) as kink coupling is varied, with the strongest effect observed when coupling is maximized.

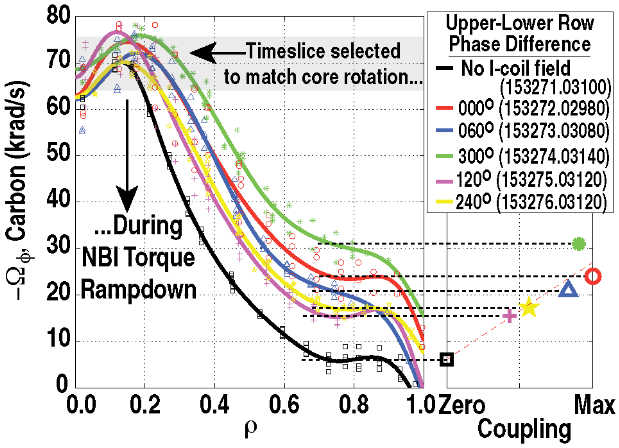

Fig. 2. Rotation profiles illustrating NTV torque effect on the edge rotation. Maximum kink-coupling n=2 fields show strongest maintenance of edge rotation.

A validated single dominant mode picture can also be applied to predicting optimal EFCC currents for any plasma scenario, regardless of 3D field source. This is achieved by nulling the kink mode coupling of the intrinsic EF [5]. Recent work has shown that an exhaustive database of over 20 experimentally determined n=1 optimal EFCC currents measured over the past 10 years is consistent with nulling the n=1 kink coupling of each individual plasma, as shown in Fig. 3. Furthermore, the kink coupling can be readily approximated by simple empirical metrics that strongly weight the Fourier harmonics of the vacuum 3D field which most drive the kink [6]. The simplicity of this approximation enables rapid computation, relying only on knowledge of the EF source geometry and basic plasma equilibrium properties (such as the shape and edge safety factor) to deliver accurate estimates of the required EFCC currents for any scenario in real-time.

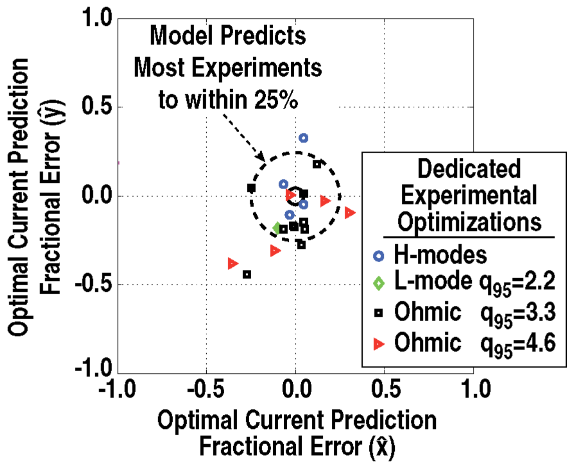

Fig. 3. Comparison of model predictions of optimal n=1 EFCC currents to experiment for 20 dedicated DIII-D optimizations conducted over the past 10 years.

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