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Physics Basis for Optimizing 3D Field Coils in Tokamaks

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The ability to predict and optimize the multimodal, non-axisymmetric plasma response to 3D fields has enabled a practical path for maximizing the benefit of 3D fields from external coils in future reactors. Ideal coupling predictions of the Generalized Perturbed Equilibrium Code (GPEC) have been validated for core locking error field correction (EFC) across a broad multi-device database [1] as well as in KSTAR edge localized mode (ELM) suppression experiments [4]. In addition, a new kinetic MHD model extension has enabled optimizations of the multi-modal plasma response for neoclassical toroidal viscosity (NTV) torque control that have been tested in DIII-D. The kinetic MHD formulation solves the anisotropic pressure perturbed equilibrium, representing the nonlinear torque as a "torque response matrix" [3].

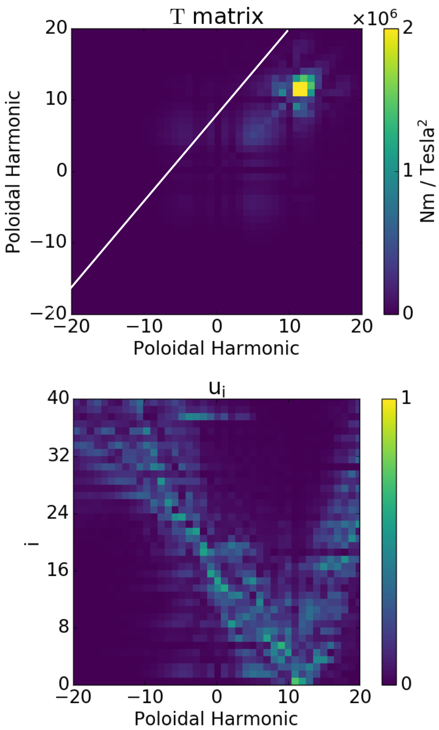

Figure 1: Amplitude of the n=2 Hermitian torque response matrix components (top) and of the corresponding eigenvectors ordered from largest to smallest eigenvalue (bottom). The first eigenmode shows is dominated by m~11 fields in this $q_{95} = 4.2$ H-mode target.

In this presentation, the eigenmodes of the resonant response matrix and torque response matrix are compared and contrasted across a wide variety of plasma scenarios. The robust features of these modes are then used together with stellarator design tools to optimize the geometry of 3D coils, increasing the efficient coupling of these coils to the physics of interest without undesired secondary effects [2]. The fields required to localize the resonant response or torque in the edge or core (minimizing the effects elsewhere) are shown to be distinct from the fields that produce the largest global responses, providing insight for the design of distinct ELM control and EFC coils. The features of a new type of quasi-symmetric magnetic perturbation (QSMP), demonstrated to induce no performance degradation in KSTAR and DIII-D experiments, are also shown.

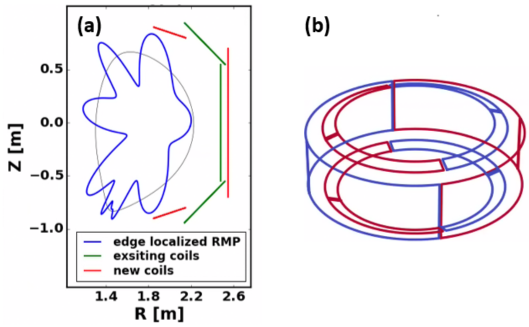

Figure 2: Location of existing 3D coil rows and hypothetical new 3D coil rows optimized for edge-localized RMP in KSTAR (a). Three-dimensional structure of the new coil (b). Figure from reproduced from [5].

Importantly, this efficient coupling can be maintained even when enforcing large distances between coils and the plasma during the design optimization. The physics-driven optimization presented here thus provides a practical path to utilizing exterior coils in future reactors to obtain the powerful 3D field benefits demonstrated on current machines with internal coils.

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