Multi-scale interactions in KSTAR disruptive plasmas with forced magnetic islands: A global gyrokinetic analysis

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Plasma disruptions remain a critical challenge for magnetic fusion devices, requiring a detailed understanding of intricate interactions to enable effective control. In KSTAR tokamak, controlled experiments using non-axisymmetric magnetic fields have revealed unexpected dynamics in disruption mitigation using non-axisymmetric magnetic fields. Specifically, an n=1 field induces a 2/1 magnetic island, triggering plasma disruption, whereas an additional n=2 field, forming an additional 3/2 island, delays disruption by up to several seconds despite earlier mode locking[1]. This robust effect has been consistently observed across multiple KSTAR discharges.

Diagnostic analyses show that the presence of both 2/1 and 3/2 islands enhances poloidal shear flow, correlating with reduced fluctuation amplitudes. These findings suggest that magnetic islands interact with micro-scale turbulence through self-generated flows, consistent with prior experimental[2], numerical[3,4,5], and analytical studies[6,7].

Using the global nonlinear gyrokinetic code GENE[8,9], we simulate KSTAR plasmas with forced magnetic islands. The results qualitatively align with experimental observations, revealing complex helical flow structures driven by the interplay of 2/1 and 3/2 islands. These flows regulate the magnitude and spatial distribution of micro-scale turbulence. Additionally, heat flux profiles are modulated by the presence of multiple islands and their relative phase differences.

This study elucidates the coupling of macro-scale magnetic islands, meso-scale flows, and micro-scale turbulence, offering insights into disruption control for KSTAR and future tokamaks like ITER. Future work will refine non-axisymmetric field configurations to optimize plasma stability.

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