COUPLING OF GEODESIC ACOUSTIC MODES AND RESONANT MAGNETIC PERTURBATIONS IN FUSION PLASMAS

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1. ABSTRACT

An analysis of the statistical spectral characteristics of resonant magnetic perturbations (RMPs), geodesic acoustic modes (GAMs), and their nonlinear coupling with ambient turbulence in the edge region of the HL-2A tokamak has been performed. Experimental observations reveal that RMPs significantly affect low-frequency fluctuations and large-scale turbulence. We present the first direct evidence that increasing RMP current weakens the coupling between GAMs and other frequency modes. Specifically, the amplitude of GAMs decreases as the RMP current increases, with larger RMP currents leading to a more pronounced suppression of GAMs. Moreover, the radial correlation length of turbulence is found to strongly correlate with the increase in RMP current and the reduction of zonal flows. These results provide new insights into the impact of RMPs on edge transport, highlighting the dominant role of the interaction between RMP-induced magnetic perturbations, GAMs, and ambient microturbulence in governing edge plasma behavior.

2. BACKGROUND AND MOTIVATION

In fusion plasmas, the interaction between plasma turbulence and magnetic perturbations has garnered significant attention for understanding and controlling plasma confinement and transport. [1-4]. In high-confinement mode (H-mode) plasmas, resonant magnetic perturbations (RMPs) have been widely used to mitigate or suppress edge localized modes (ELMs), and to correct error filed , recently attracting significant attention within the fusion community. The application of RMPs inevitably induces interactions among magnetic perturbations, microscopic turbulence and zonal flows, ultimately influencing the overall plasma performance.

3. KEY FINDINGS

We begin by estimating the spectrum of background turbulence to illustrate how turbulent behavior varies under the influence of external fields. The local wavenumber-frequency spectra $S(K, f)$ for conditions with and without RMPs were derived using data from two probes poloidally separated by 7 mm (or 8 mm) at $\rho\approx0.92$ and are presented in Figures 1(a) and 1(b), respectively. As shown in Figure 1(c), the background turbulence exhibits a dispersion relation characteristic of drift waves rotating in the electron drift direction. When the RMP is off, the power distribution in the spectrum is more concentrated, with higher peak values. Conversely, when the RMP is activated, the wavenumber spectrum becomes relatively flatter, and the peak position shifts toward lower wavenumbers. Figure 3(d) illustrates that the RMP has a significant impact on low-frequency fluctuations (f < 50 kHz) or large-scale turbulence, while high-frequency fluctuations remain largely unaffected. These results from spectral analysis indicate a pronounced influence of RMPs on low-frequency fluctuations and large-scale turbulence.

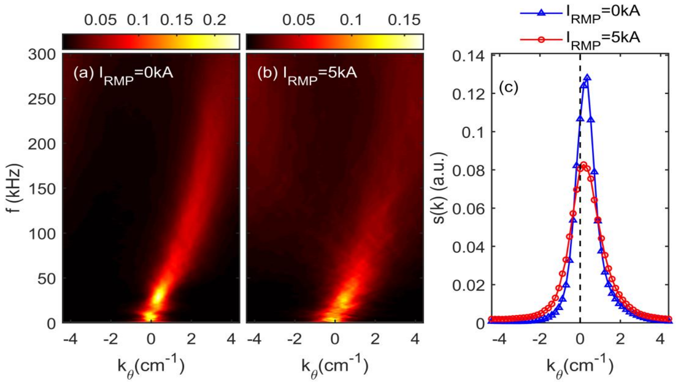

Figure 1. (a) Wave number-frequency spectrum when the RMP is applied (I_{RMP} = 5kA) and (b) when the RMP is turned off. (c) Wave number spectrum and (d) frequency spectrum under both RMP conditions (I_{RMP} = 0KA, 5kA).

Figure 2 illustrates the self-bispectrum calculated from the electric potential ϕ at $\rho \approx 0.92$ under different RMP currents. Panels (a-d) display the self-bispectra $\hat{b}^2_{\phi\phi\phi}(f_1, f_2)$, while panel (e) presents both the self-bispectrum and the bispectrum $\sum\hat{b}^2_{\phi\phi\phi}(f)$ (See Appendix). In panel 4(a), a significant coupling is observed between the ~8 kHz GAM and the turbulence above 200 kHz. However, this coupling diminishes in panels (b) and (c), becoming evident only within certain frequency ranges. Specifically, when compared to the RMP-off condition, the coupling between the turbulence over 200 kHz and the GAM is suppressed at RMP currents of 2 kA and 3 kA. In panel 4(d), at an RMP current of 4 kA, the coupling between the turbulence and the GAM nearly vanishes, a trend also reflected in the results presented in panel 4(e). As shown in panel 4(e), the strongest three-wave coupling occurs near 8 kHz when RMP is off. However, this coupling intensity decreases at RMP currents of 2 kA and 3 kA. At 4 kA, the coupling level around 8 kHz is comparable to the noise levels observed at other frequencies, indicating a substantial suppression of the three-wave coupling. Overall, increasing the RMP current appears to weaken the coupling between the GAM and other frequency components.

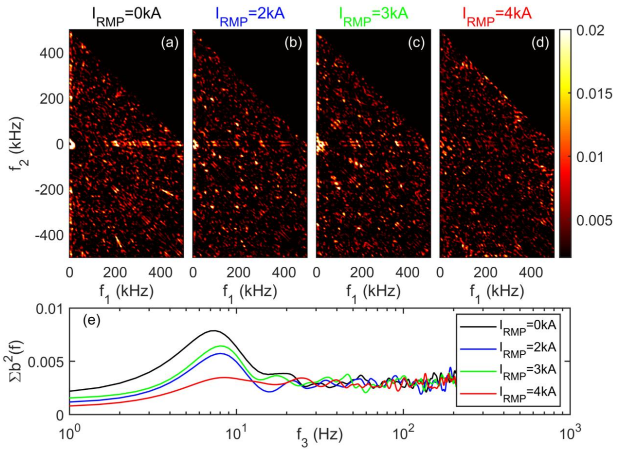

Figure 2. Self-bispectra calculated from the electrostatic potential at ρ ≈ 0.92 under different RMP currents (a-d), along with the self-bispectrum and cross-bispectrum (e).

4. IMPLICATIONS AND FUTURE OUTLOOK

This study analyzes the effects of RMP on GAMs and background turbulence in the edge region of the HL-2A tokamak plasma, focusing on their interactions with GAMs and the nonlinear coupling with ambient turbulence, as well as the spectral characteristics associated with varying RMP currents. Experimental observations provide the first direct evidence that RMPs has significant effects on low-frequency fluctuations and relatively high-frequency turbulence fluctuations. As the RMP current increases, the RMP weakens the coupling between the GAM and ambient turbulence fluctuations at other frequencies, primarily due to the damping effect of RMPs on GAMs, ultimately leading to a reduction in coupling strength.

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