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Cold-hot coupled waves in a flowing magnetized plasma

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In magnetic confinement experiments, a transient collective plasma flow occurs in the relaxation event of magnetohydrodynamic (MHD) modes such as the internal kink [1], tearing modes [2], and edge-localized modes (ELMs) [3]. The flow induces a transient plasma current, which then generates electromagnetic (EM) waves via the Maxwell equations. In this work, we analyzed the waves associated with the collective particle transport to gain more understanding on the MHD relaxation dynamics. Describing the time-dependent flow motion as cold waves, we obtained a generalized dispersion relation containing cold, hot, and cold-hot coupled waves. The analytic description shows that generation of the nonlinearly coupled harmonics depends on the cold and hot wave dispersions. The waves propagating in the direction of the flow undergo spectral broadening by the Doppler effect. Fully kinetic particle-in-cell simulations corroborated these theoretical predictions.

To derive the generalized dispersion relation, we use a plasma distribution function that takes into account a total particle motion in the flow. Integrating the linearized Vlasov equation along a perturbed phase-space trajectory yields the first order distribution function from the given zeroth order function. The first moment of the distribution gives the perturbed current density, which leads to the generalized hot wave dispersion relation via the Maxwell equations. The dispersion relation has wave-particle resonances at $\omega = n\omega_{cs} + \sum_l m_l\tilde{\omega}_l + \mathbf{k}\cdot\mathbf{u}_s + k_\parallel v'_\parallel$, where ω is the wave frequency, ω_{cs} is the cyclotron frequency of the species s, $\tilde{\omega}_l$ is the lth cold mode frequency, $\mathbf{k}$ is the wavenumber, $\mathbf{u}_s$ is the time-averaged flow velocity, $v'_\parallel$ is the random particle velocity parallel to the external magnetic field, and n and m_l are integers. In the right-hand side, the first two terms indicates the cold-hot coupled harmonics and the third term indicates the Doppler effect.

Figure 1 shows an example where the wave propagation is perpendicular to the external magnetic field ($k_\parallel \to 0$). The dispersion relations obtained from the Vlasov analysis show good agreements with the PIC simulation results. The cold-hot coupled harmonics are clearly demonstrated when the time-varying plasma flows exist (the middle and right panels). The frequency spectrum in the middle panel shows the additional coupled harmonics to the cyclotron harmonics. The spectrum in the right panel (finite $\mathbf{k}\cdot\mathbf{u}_s$) shows spectral broadening because the harmonic frequencies are continuously Doppler-shifted. Furthermore, the PIC simulations show that the time-varying flow increases the total field intensity in the plasma and broadens the frequency spectrum by cold-hot coupled waves.

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We found that the wavenumber and the time-averaged velocity of the plasma flow determine the cold-hot coupled harmonics and the Doppler effect, respectively. This finding implies that the wave spectrum can contain information about plasma flows. The combination of the generalized dispersion relation and the PIC simulations will help develop insights into the transport phenomena associated with MHD relaxations [4] and energetic particles [5]. We are extending the kinetic analysis and simulations for the convective transport during an ELM crash [3] to develop physical interpretations of whistler-frequency waves that we routinely observe in ELM crashes on the KSTAR.

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