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Simulation of Compressional Alfvén Eigenmodes in Tokamak Disruptions and Impact on Runaway Electron Transport

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Alfvénic modes in the current quench (CQ) stage of tokamak disruption have been observed in both DIII-D and ASDEX Upgrade experiments. In DIII-D the excitation of the mode is linked to the presence of high-energy runaway electrons (REs), and a strong mode excitation is often associated with the failure of RE plateau formation. The Alfvénic instabilities are being explored in order to devise a complementary strategy for RE mitigation in addition to impurity injection for ITER and other tokamaks.

In this work we present results of self-consistent kinetic-MHD simulations of RE-driven compressional Alfvén eigenmodes (CAEs) in DIII-D disruption scenarios, providing an explanation of the CQ modes. We use the kinetic-MHD code M3D-C1-K [1] to simulate the excitation of CAEs driven by REs in the disruption case.

We conducted a series of linear simulations for the n=1 mode with varying peak RE energy. It is found that the frequency of the excited most unstable mode follows a staircase-like function with RE energy, and the spacing between adjacent modes is about 0.2-0.4 MHz. The mode frequency and the relationship with RE energy are consistent with DIII-D experimental observation, as shown in Fig. 1. However, the highest mode frequency we found is around 1.4 MHz, which is smaller than in the experiment. Each level of the staircase represents a different mode structure in the poloidal plane. Analysis of the simulation shows that the mode has dominantly compressional polarization ($\delta B_\parallel \gg \delta B_\perp$), which is also consistent with the recent diagnostic result.

The simulation results can be explained by considering the resonance between the trapped REs and the CAEs [2]. The trapped REs affected by gradient drifts and mirror forces from $\delta B_\parallel$ will have a net change of canonical angular momentum (P_ϕ), which can cause the trapped particle orbit to shift in the radial direction. This resonance mechanism indicates that a radial gradient of the trapped REs can lead to a drive of the mode. Unlike the transit frequency of REs, which only depends on particles' velocity, the precession frequency of trapped REs is proportional to the relativistic RE energy, therefore the higher frequency mode can only be excited when high-energy REs are present.

We also did nonlinear simulations using a broad RE energy spectrum and study the spatial diffusion of REs driven by the mode exciation. However, we found that the diffusion effects from CAEs are too weak to explain fast RE loss observed in experiments. We found that in order to reach a short RE diffusion time of a few milliseconds, the perturbed $\delta B_\parallel$ must be larger than 0.5 Tesla. To reach such a high level of the mode amplitude, more trapped REs are required, which may come from other pitch angle scattering mechanisms than high-Z ion collisions, including the avalanche generation and turbulence scattering.

In summary, the excitation of current quench Alfvénic mode can be explained by considering the resonance between CAEs and the precession motion of trapped high-energy REs, and can be reproduced using kinetic-MHD simulation. There is still a discrepancy with the experiments on the RE diffusion, which will be further studied by updating the model with more kinetic effects.

References

[1] Liu, C., et al., Comput. Phys. Commun. **275**, 108313 (2022).
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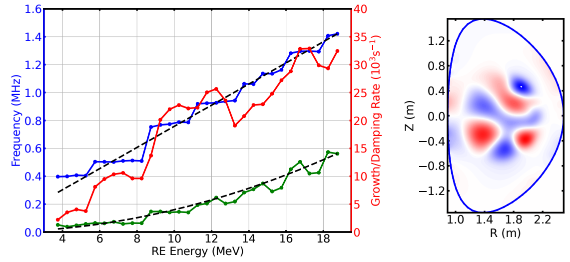

Figure 1 (left) Linear simulation results of excited CAE mode frequency (blue), growth rates (red) and damping rate (green). (right) Mode structure of CAE (f=0.9MHz)